HAWAIIAN PLANTERS' RECORD

Vol. LIV 1954 No. 4

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PREFACE

About 57 per cent of the land area in cane in Hawaii is irrigated. This area is responsible for a little less than two-thirds of the total production of sugar. Over 40 millions of dollars were expended in the early days of the industry to establish the irrigation systems on those plantations where irrigation is necessary to grow cane. This capital investment would be many times the original figure if the systems were to be installed under present conditions. At the moment, it takes about one ton of water to make one pound of sugar on the irrigated plantations of Hawaii. These figures illustrate quite vividly the importance of water in the Hawaiian sugar industry.

Since the advent of the irrigation ditches to bring water to the drier areas for the production of cane, the know-how in soil technology, plant-water relationships and water utilization has advanced both rapidly and broadly. The Experiment Station of the Hawaiian Sugar Planters' Association has always been cognizant of the many problems associated with irrigation in the production of cane, and has embarked recently on a concentrated research program aimed at increasing the efficiency of water usage in the production of sugar.

It is proper at this time, therefore, to evaluate what has taken place in the irrigation of cane in Hawaii, to point out problems, and to discuss thoroughly and objectively any differences of opinion that may exist in regard to the over-all objective of obtaining the most efficient utilization of water. The purpose of this seminar was to review the history of irrigation in Hawaii, how water has been developed, how it is being used on the plantations, and how further research can contribute to a better understanding of irrigation practices. This series of papers published in this issue of the Hawaiian Planters' Record should stimulate the objective thinking that is necessary not only for good research, but also for the effective application in the field of the results of that research.

May this seminar be a milestone in the progress of irrigating sugar cane in Hawaii!

L. D. Baver

A BRIEF HISTORY OF IRRIGATION INVESTIGATIONS IN HAWAII

H. A. WADSWORTH[1]

The irrigation history of Hawaii is a compelling subject. Fragments which contribute to it are hidden away in hundreds of records in the libraries and archives. Illuminating sidelights come from the rapidly decreasing number of *kamaainas* who lived through the early days or who heard them discussed while young men.

Parts of the completed tale have been told. But an irrigation history, written to trace the effect of an agricultural practice upon the economic and social development of a community, cannot be expected to elaborate upon scientific studies which made that practice grow and prove itself. The cataloging of the sequence with which major engineering works were undertaken is interesting for the record; but there is little space in such an account for details of the experimental successes and failures in irrigation studies which made those engineering works necessary (1) (2).

This short history is a contribution to the completed story. It will attempt to trace the path of scientific thinking and experimental work in the development of our current practices.

Histories cannot be written of developments still in motion. Competent accounts can only be framed after chapters are finished and their contributions viewed with detachment. Several such chapters suggest themselves. First of these is the arduous period from the time of the early irrigation efforts on the Pierce Company plantation at Lihue in 1856, to the establishment of the HSPA Experiment Station in 1895. A comprehensive paper by W. P. Alexander in 1923 summarizes the experimental work in irrigation during the next quarter of a century. In 1937, H. R. Shaw and J. A. Swezey compiled the results of irrigation work during the fourteen years thereafter.

A new chapter was begun in about 1945. New devices for soil moisture control were imported and new physiological concepts developed. A historical presentation of the use and value of these new tools will have to wait until a proper perspective is established. Proponents of these tools and concepts will contribute to the seminar to which this paper is an introduction.

WATER LAW IN HAWAII

Irrigation in Hawaii is older than the memory of man; certainly no legends report the completion of the first *auwai* and the ceremonies that marked the

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irrigation of the first taro patch. But it was a significant occasion. It demonstrated a practice that was to permit the full development of the Hawaiian people. And it incidentally pointed the way to the commercial irrigation of sugar cane which came several hundreds of years later.

It is interesting to note that the concepts of water rights in Hawaii developed in complete isolation from the legal codes in Europe and America. In general, irrigation law in Eastern United States springs from the Common Law of England with its concept of riparian rights, entirely inappropriate as far as irrigation is concerned. In Western America, the doctrine of appropriation prevails. Title to the water in living streams remains with the State; cost-free licenses may be secured for beneficial use. Neither of these principles is used in Hawaii.

It is hardly surprising that this difference should exist. The pattern in Hawaii was fixed in an atmosphere of complete feudal control; the right to use land and water was at best permissive. Title remained firm in the hands of the King and his chiefs.

Through the actions of a wise and generous king, title to a large part of the land and water was removed from the king and given to individuals who had actually lived upon the land and used those resources. This liberal action, commonly known as the *Mahele*, distributed a large percentage of the land in the islands among chiefs and commoners. Title to the water used on the land at the time of the *Mahele* was transferred with the land. Nowhere else under the American flag does such a situation exist. And in this peculiarity is both strength and weakness for the sugar industry. If the using corporation has acquired title to the water necessary for its operation, through purchase or by original grant, political pressure cannot successfully jeopardize that right. If the user must lease his water privileges from the current owner, he must, at specified intervals, compete for its continued use with other potential users.

It is not surprising that this unusual situation should be challenged. In 1904, Theodore Roosevelt sent James R. Garfield, son of the martyred President, to Hawaii to study the peculiarities of the Hawaiian water code and to recommend changes which would be desirable to bring it into conformity with the continental pattern. There is no public record of Mr. Garfield's recommendations. Perhaps he reported that no change was necessary; certainly none was made.

In 1915, Governor Pinkham of Hawaii appointed a committee of three competent residents to make the same sort of study and to recommend changes in the law, if thought desirable, for legislative approval. After an elaborate review and consultation with an outstanding water-law authority in California, the committee recommended no change.

The pattern seems fixed. To acquire the privately-owned water rights for public administration would be prohibitively costly. It should be said perhaps that the concept of water rights described above relates to surface water only. The rights to ground water are not so well codified.

THE BEGINNING OF THE SUGAR INDUSTRY

It was in this atmosphere of indefinite titles that the sugar industry found its beginning. The Ladd and Company plantation at Koloa was organized in 1835. Four others were reported as operating in 1852. Such plantations were simple and flexible organizations. New ventures were frequently begun but others would go

out of business. The net growth was slow. The mills were correspondingly simple. In his inaugural address before the Royal Hawaiian Agricultural Society in 1851, William E. Lee called the mills "screeching nuisances" and directed the thinking of the Society to other crops.

Detailed accounts of these early plantation operations have been lost. But it seems clear that none was irrigated in the sense that we now use the term. Irrigation of sugar cane as a commercial crop began with the construction of the Rice ditch on Kauai in 1856. This ditch, simple by present day standards, prompted similar development on other islands, particularly on Maui. The sequence followed in this promotion cannot be a part of this brief account. It has been told elsewhere (3).

But it should be said that by 1882, when the publications of the Planters' Labor and Supply Company began its continuing record of the expanding sugar interests, the economic justification of costly irrigation works for cane sugar production had been established. During this period, the costly early ditches on Maui had been constructed by the Alexander and Baldwin interests, the waters of Iao Valley had been diverted for sugar irrigation near Wailuku and significant development was under way near Lahaina.

Because of this increasing interest, the first issue of the Planters' Monthly devoted much space to problems involved in this new tool in sugar production. In this issue, H. M. Whitney requests information as to "the modes practiced (in irrigating) and how often cane should be irrigated." A letter from H. P. Baldwin published in the same number opens the long debate as to the proper distribution of an inadequate amount of water between plant crops and ratoons. Students of irrigation methods will find interest in a paper by Geo. W. Willfong entitled "Twenty Years Experience in Sugar Culture." Here the manager of one of the units that subsequently became the Wailuku Sugar Company describes an experiment in planting for irrigation. This experiment involved planting on the contour and "striking a water level for each line." No mention is made of any other method used perhaps as a check or control in the experiment.

Other items lifted largely at random from the Planters' Monthly show the enthusiasm of the times. For example, "Investigator," contributing to Volume 8 in 1889, urges plantations "to make the simple change to irrigation," if there is a scarcity of rainfall. And in another short account there is the recommendation that cane pieces be planted lengthwise in the furrow with the butt end pointed uphill. The reason given was that the cane shoots would be less subject to damage by the force of the water if planted in this manner.

The entire array of fourteen volumes of the Planters' Monthly from its inception in 1882 until it became the Hawaiian Planters' Record, published by the Hawaiian Sugar Planters' Association, provides unexcelled material for students of the sugar industry in Hawaii. The frequent papers on irrigation illustrate the vision and sharp powers of observation in the local irrigation pioneers.

In one of the late issues of the Monthly a sugar chemist proposes the establishment of an industry-wide experiment station to explore some of the problems which had been debated in earlier volumes. Although in his list of problems needing experimental work, there was no mention of irrigation work, problems in this field demanded much of the attention of the newly formed station in its early years.

THE EXPERIMENT STATION, HSPA, BEGINS ITS WORK 1895–1923

Since the findings of the new Experiment Station were published in the Planters' Monthly for fourteen years before the old journal was abandoned, a new tone of scientific precision began to appear in the later issues.

For example, Dr. Maxwell, the first Director, reported in 1896 on the water-holding capacity of Hawaiian soils and a year later reported on a study of transpiration losses from sugar cane in Honolulu.

Neither space nor time will permit a complete review of all the irrigation papers in the Monthly during the early years of the Station or in the Hawaiian Planters' Record which took its place in 1909. These contributions have already been abstracted for the casual reader (4); the originals are readily available to the student who demands primary sources.

But some of the reports deserve recounting since they seem to relate to current thinking. For example, Crawley continued his studies in the water-holding capacity of soils and directed attention to the fact that soils in the field may exhibit different water-holding capacities than would be observed if the samples were removed for laboratory determination. He also proposed a program of soil moisture sampling as a means of irrigation control.

In the same year C. F. Eckart, then Director of the Station, reported results of an experiment to determine the water requirement of sugar cane. In this study ". . . daily readings are taken of the soil moisture in these tests with a soil hygrometer, the electrodes of which are placed at a depth of one foot in the furrows." There seems to be no further information available with respect to this challenging instrument.

Director Eckart was seriously concerned with irrigation and he must have been a tremendous worker. His papers run through the record of the times. Some of these deal with the effects of salt in irrigation water, others with the effects of fertilizers and lime upon water requirements, while others attempt to determine desirable applications of water by observations upon the temperature and relative humidity at the time. Apparently Mr. Eckart assumed that the normal irrigation interval was one week; his computations were directed toward the determination of the amount of water that should be applied after each seven-day interval.

As a result of these studies and others, Mr. Eckart proposed desirable irrigation applications at the assumed weekly interval. The protests by plantation managers run through many subsequent issues. One of them said that he did not see how cane could be kept alive with such meager allotments.

Irrigation investigations were intensified in 1916 by the appointment of R. M. Allen as Assistant Agriculturist in the Experiment Station. Mr. Allen came from the University of California where studies in soil moisture and plant relationships were beginning to receive intensive investigation. As a result of field studies which included a program of soil moisture sampling, Allen discussed the "optimum moisture percentage" for soils at Waipio and later suggested that soil moisture percentages between 25 per cent and 30 per cent were "optimum" for the soil under consideration. Allen's resignation from the Experiment Station to accept plantation employment brought an end to his researches in 1920.

However, the work suggested by Allen was continued by Guy R. Stewart who joined the Experiment Station in 1921. Mr. Stewart discussed the critical soil

moisture contents which figured prominently in the literature of the times. Although he reported his determination of the hygroscopic coefficients, optimum moisture contents and maximum water-holding capacities for eight Hawaiian soils, he made no actual determination of the permanent wilting percentage although he discussed its significance.

In the meantime, work had been proceedingly slowly in studies on methods of distributing irrigation water and in the determination of appropriate irrigation intervals. Papers appeared on irrigation methods during the annual meetings of the Association, but in general they were descriptions of the old contour line method which gained early popularity. However, two significant contributions should be noted.

In 1922, H. W. Baldwin announced the use of wooden flumes in the fields of Hamakuapoko in place of the usual earthen water courses. Cane was planted in relatively long lines on slopes of from one to three percent. Moreover, these lines were laid in a "herringbone" array to reduce the necessary internal flume to a minimum. During the next year, the establishment of a sprinkler system for sugar cane at Hawi was reported by J. S. B. Pratt, Jr.

Apparently, formal tests for the desirable irrigation interval were first reported in 1914. The tests, conducted at Waipio, were designed to study the water requirements for seven cane varieties which were prominent in the planting program at that time.

As has been suggested, irrigation development in Hawaii was exhaustively summarized by Wm. P. Alexander in 1923. His paper forms a convenient milestone in the over-all review of the subject. Moreover, it is a valuable source book for students of sugar cane irrigation.

PRE-WAR AND WAR-TIME STUDIES
1923–1945

The early years following the publication of Mr. Alexander's paper resulted in an unprecedented number of papers on irrigation. These contributions have been abstracted elsewhere. It need only be said that studies of soil moisture histories under irrigation were vigorously prosecuted under the authority of a cooperative agreement between the Experiment Station and the Waimanalo Sugar Company. This work was reported in detail until 1927 when the work was either abandoned or suppressed. Subsequent reports from the Waimanalo cooperation deal with problems in water measuring and seepage prevention in open ditches.

As might be expected, Mr. Alexander continued his interest in irrigation. In 1928, Ewa Plantation Company reported an effective control of irrigation interval which was based primarily upon rates of cane growth.

At about the same time, H. R. Shaw joined the Experiment Station staff and made an exhaustive series of studies of methods of irrigation, practices in interval control and water measuring programs of five intensively irrigated plantations. Mr. Shaw played an important part in irrigation research until the outbreak of the war.

In 1928, the influence of the California studies in soil moisture relationships and transpiration studies began to be apparent in the local scene. Wilting point determinations were made on a soil from Waipio in the Keeaumoku Street greenhouses and subsequently on a wide variety of plantation soils at Waipio.

At about the same time carefully-grown sugar cane plants were established in large tanks of screened soil at Waipio. Each of these tanks held about one ton of soil; facilities were provided for weighing the tanks at frequent intervals. Preliminary studies with the soil identified the maximum field capacity and the permanent wilting percentage.

When the plants had reached an age of about six months, covers were fitted to each tank so that evaporation losses from the soil could be eliminated. The cane stalks emerged from holes in the center of the covers. Spaces between the stalks, and between the stalks and the sides of the holes, were caulked with machinist's waste.

Each tank was irrigated to the weight associated with its maximum field capacity, lids were fitted in place, and the total length of cane stalks measured to the nearest millimeter. In this work, the total in any tank was the sum of the lengths for all the stalks in that tank. Measurements were made from a permanent datum on the tank to the last visible ligule on each stalk. Plotting the total lengths against time gave a picture of the growth of the plant.

At the same time, daily or bi-weekly weighings of the tanks provided a direct measure of the water used by transpiration. Increases in the tare weight of the tank due to increasing plant weight were thought to be negligible between successive weighings. The tare weight of the system, required for the determination of the gross weight at maximum field capacity, was adjusted frequently by weighing plants of equal age grown under similar conditions. Plotting the gross weight of the tank against time gave evidence of the rate at which water was being used by transpiration. A straight line, of course, indicated a uniform rate of loss.

The observations described above were continued for almost 18 months. In all cases, the rates of transpiration were constant between the gross tank weight associated with the soil at maximum field capacity and that associated with the soil at the permanent wilting percentage. It should be said that the gross weight at permanent wilting percentage was identified by the taking of soil moisture samples from the soil volume occupied by roots, at an appropriate time.

Moreover, the growth history of all the plants indicated a uniform rate of elongation as long as the moisture content was between the limits mentioned above. During the first season of growth the discontinuity between growth and no growth was marked and easily identified. Growth essentially ceased when the weight of the tank was reduced to that associated with a soil at the permanent wilting percentage. During the second season, the discontinuity was not so pronounced but the reduction in rates could be identified after a few days of soil moisture deficiency.

Some of the tanks were irrigated so infrequently that the soil moisture within the root zone was allowed to move through the entire range from maximum field capacity to the permanent wilting percentage. Others were irrigated so often that the soil moisture was always within the upper quarter of the available range. No differences in rates of growth were noted; nor were there significant differences in cane and sugar yields at harvest.

The peculiar growth response of old cane to deficient soil moisture has been noted. Another observation should be mentioned. Occasional showers frequently resulted in increases in the gross weights of the tanks which seemed out of line

with the possibilities of leaks through the seals which were being constantly improved as experience was gained.

A fantastic seal was developed on one tank after soil moisture samples had been taken at three-inch increments. The system was then sprinkled for four hours by a garden sprinkler suspended over the plant. A gain of 71 pounds was noted as a result of this operation. There was no evidence of a leak through the complicated seal. Soil samples taken after this treatment showed a significant build-up of soil moisture below the surface foot. There was no increase in moisture content in the surface foot of soil in the tank.

No defendable explanation was given for this observation, which was the most spectacular but not the only one which was significant. But the report did direct attention, for some time, toward the effect of light showers and dew in an irrigation program. The financial depression in the early 1930's resulted in the abandonment of this tank farm.

Other concurrent studies concerned the diurnal variations in the moisture content of the cane stick under differing environmental conditions. In a report on one of these studies in 1941, it is suggested that the moisture content of a carefully specified part of the cane plant might be used in the determination of the appropriate irrigation interval.

It soon became apparent that the effectiveness of any irrigation method depended upon the distribution of soil moisture which could be secured. Mr. Shaw reported the results of a long series of plantation studies with long line methods. In these studies frequent observation pits were dug along the center line of the furrow and the depth of penetration of water carefully plotted on sheets which also carried the profile of the line under study. In addition, transverse trenches, cut across the line at the upper, the middle and the lower ends, gave evidence of the lateral seepage which was being secured. In most cases the patterns so secured indicated only fair distribution of water.

Since the length of a line to be irrigated in this way depends upon the seepage characteristics of the soil in question, as well as the grade of the line, methods were devised for quantitative measure of this important property under field conditions.

Mr. Shaw's resignation from the Experiment Station and his appointment as irrigation supervisor at Waialua Agricultural Company permitted the expansion of the argument, developed in the tank farm, to field conditions. Under the authority of a cooperative agreement between the Experiment Station and the plantation, test areas were established in six typical environments. Detailed cane growth measurements and daily soil moisture determinations seemed to demonstrate the possibilities of their use in plantation irrigation control.

At the conclusion of the cooperative agreement, the Waialua Agricultural Company embarked upon an ambitious program. The entire plantation was surveyed in such a way that soil samples could be secured from carefully specified areas of about two acres each. The samples were studied in the laboratory for the determination of the maximum field capacity, through the use of the moisture equivalent centrifuge, and for the permanent wilting percentage. Test lines of cane were specified for continuing growth measurement and soil moisture determination. Short cuts in this elaborate procedure on a plantation scale were finally effected. As a result of one of these methods, which involved the use of a specially

designed balance, each section overseer is now informed at frequent intervals of the number of acre inches of water per acre that are available for plant use in each of his fields. Irrigation intervals are determined from this figure. It is, of course, implicit in this argument that the lower limit of readily available water is the permanent wilting percentage.

The high cost of operating the program tended to discourage the spread of this procedure to other plantations.

In the meantime, Dr. U. K. Das in a short but highly provocative paper suggested that his new concept of "day-degrees" might be used to determine irrigation intervals. The problem was to determine the number of day-degrees that should be allowed to accumulate before an irrigation was ordered. During the period between 1936 and 1948, at least 21 experiments designed to supply this important but elusive figure were reported in the literature. It is probable that many other day-degree studies are to be found in plantation files. Interest in this approach waned after 1948.

Concurrently with the day-degree studies mentioned above was the beginning of efforts to get some measure of the moisture status of soils in sugar cane fields without the cost and tedium of soil moisture sampling. Ewa Plantation Company became interested in an electrical-resistance device developed by Dr. G. J. Bouyoucos at Michigan State College. The plantation purchased the necessary plaster of Paris blocks, an appropriate source of electric energy and a Wheatstone bridge in 1940. Tests with this equipment proved unpromising at the outset and in 1941 the apparatus was moved to Waipio. Here the device continued to give erratic and inconsistent readings. A summary of the local results was sent to Dr. Bouyoucos. His only comment was that a saline condition was probably responsible. The outbreak of the war brought an end to this early study of the use of the Bouyoucos blocks in determining irrigation interval. As will be noted later in this seminar, this device was subjected to renewed investigation at a later date. In 1940, Russell Wold developed a so-called "moist meter" for the purpose of giving an index of soil moisture without the need of taking samples. This device was based upon the relative differences in thermal conductivities of wet and dry soils.

Maximum effort had previously been expended in determining the irrigation interval which would result in maximum cane tonnage. The suggestion that the best interval for maximum cane yield might not be the best interval for the most economic production of sugar was made in 1936. As a result, the productive cooperative agreement between the HSPA Experiment Station and Waialua Agricultural Company was continued. In a well-replicated experiment, under the authority of this cooperation, one treatment was irrigated when the permanent wilting point had been reached. Another treatment suffered four days of relatively unavailable soil moisture. Another treatment was allowed to stand for eight days after the permanent wilting percentage had been reached before the plots were again irrigated. As might be expected cane yields were smaller on the plots which received the delayed irrigations. But the juice quality in those plots was better. There was no statistical difference in tons of sugar per acre between any of the treatments, and the evident economies in water and labor were impressive.

It should not be inferred from this detailed account of studies in irrigation control that work in the mechanics of getting water to the cane plants had been

neglected. The irrigation flume reported by Baldwin in 1922 was improved at Waialua Agricultural Company through the use of precast concrete sections and more positive discharge ports. In spite of its costs and immobility, this method, used in conjunction with carefully surveyed long lines, became standard practice on many plantations for many years.

The possibilities of irrigating sugar cane by overhead sprinklers were re-explored by Waialua Agricultural Company in 1940 in spite of previously unsatisfactory results at Kohala, Ewa and Waipio. A field of 105 acres was provided with an underground system of pressure lines served by a heavy-duty, electrically-driven pressure pump which secured water from a cement-lined canal that bounded the field on the upper side. Strategically located valves were provided on these buried lines so that surface pipe sections could be attached. Actual distribution was accomplished from riser pipes carrying conventional rotary sprinklers which were connected to these surface pipes. The cane lines themselves were straight, regardless of topography, so that machine operations might be facilitated.

Although a decided saving in the water required for irrigation by this system was noted and although all field operations were greatly simplified, the system was never expanded into plantation practice. A complete analysis of the costs of and returns from the system was made after all figures were in but no statement was ever published.

The development of giant rotary sprinklers by the United Fruit Company caused the subject to be reopened in 1947. Sprinklers capable of serving about three acres at each setting were borrowed from the United Fruit Company and established on high-capacity pressure lines in a small valley near Waialua with the thought that the effects of wind might be minimized in that area. In spite of this precaution, the distortion of the pattern was so great that acceptable coverage was not obtained. The cost on an acreage basis was great. This study was soon discontinued.

Other plantations were engaged in a search for alternate materials for the heavy concrete flume which had been developed at Waialua Agricultural Company and used extensively by other plantations. Paper impregnated with a plastic material was used at Ewa Plantation Company. The difficulty of getting the water out of the paper-lined section was great.

Some plantations turned to the fabrication of light flumes from thin aluminum sheets. Methods of protecting the metal from the electrolytic action resulting from the contact of the metallic aluminum with iron-rich soils were devised. Devices for removing water from the flumes, in controlled amounts, at spacings in step with the normal distances between cane lines, are under intensive study.

The development of light-weight aluminum flume has permitted the lengthening of the cane lines indefinitely. Auxiliary supply flumes cross the field at intervals determined by the grade of the line and seepage characteristic of the soil. Water is added to the lines when needed. The flumes can be readily removed at harvest time. At present this practice finds its greatest usefulness at Olokele Sugar Company, Ltd. and The Lihue Plantation Company, Ltd.

CURRENT STUDIES

Implicit in the argument that irrigations may be delayed until the soil has been depleted to the permanent wilting percentage is the assumption that soil

moisture is equally available at all moisture contents between the maximum field capacity and that lower limit. This argument had been stoutly defended by some mainland workers. Moisture content-surface force curves were studied to find physical justification for this concept. The rate of growth curves at Waipio and elsewhere and the rate of transpiration studies in the Waipio tanks gave support for this basic argument in Hawaii.

Recently this argument has been challenged by workers in Hawaii and in Continental United States. And it does seem clear that the assumption of equal availability finds support only as a first approximation of the surface force curves. Field tests with sugar cane, and more recently with pineapples, indicate that this first approximation is not adequate for the maximum yield of these crops. Such evidence suggests that irrigations should be so timed that the moisture tension in the soil would never exceed about four atmospheres according to one school of thought and something less than one atmosphere according to another. It should be noted that the soil moisture tension at the permanent wilting percentage is assumed to be about 15 atmospheres.

Apparently the turning point in the situation is the shape of the soil moisture-surface force curve for the soils under consideration. These curves are now being plotted by skilled laboratory technicians working with ingenious apparatus.

Moreover, new field devices are being used to measure functions of moisture contents in the field. Purpose is to secure information with respect to the moisture status immediately without the cost and tedium of soil sampling. One of these involves the use of blocks of plaster of Paris with appropriate electrical connections buried in the soil. These Bouyoucos blocks were studied during the early years of the war. Apparently values are to be found in this approach to the soil moisture problem which escaped discovery at that time.

Another device is the tensiometer which gives evidence of relative soil moisture tension on a dial built into the instrument. Although this device fails to operate when the tension exceeds about one atmosphere, tensiometers are in wide use in some areas.

As has been indicated, the new approach to the basic problem involving the description and interpretation of surface force curves for Hawaiian soils and the evaluation of instruments for the quick and accurate determination of soil moisture status is too young and too controversial to rate inclusion in a history. One of the purposes of this seminar is to explore the possibilities in the new thinking and to capitalize upon them. A history of irrigation investigations in Hawaii written in 1963 will lay great stress upon the results of this seminar.

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WATER DEVELOPMENT FOR HAWAIIAN SUGAR CANE IRRIGATION

DOAK C. COX[1]

INTRODUCTION

Water development may be defined as including the artificial diversion, transportation, and storage of water for man's uses. The nature of a system of water development in any area is dependent upon the geology and hydrology of the area, the nature of the uses for which the water is wanted, and the status of technology. The Hawaiian Islands are semi-tropical, mid-oceanic, volcanic islands in youthful to mature stages of erosional development (8). Implicit in this statement is a complete, though general, description of both their geology and their hydrology (9).

Geology

The mid-oceanic volcanoes are predominantly basaltic. Each of the major Hawaiian Islands consists of one to five volcanic domes (5). (Figures 1 and 2)

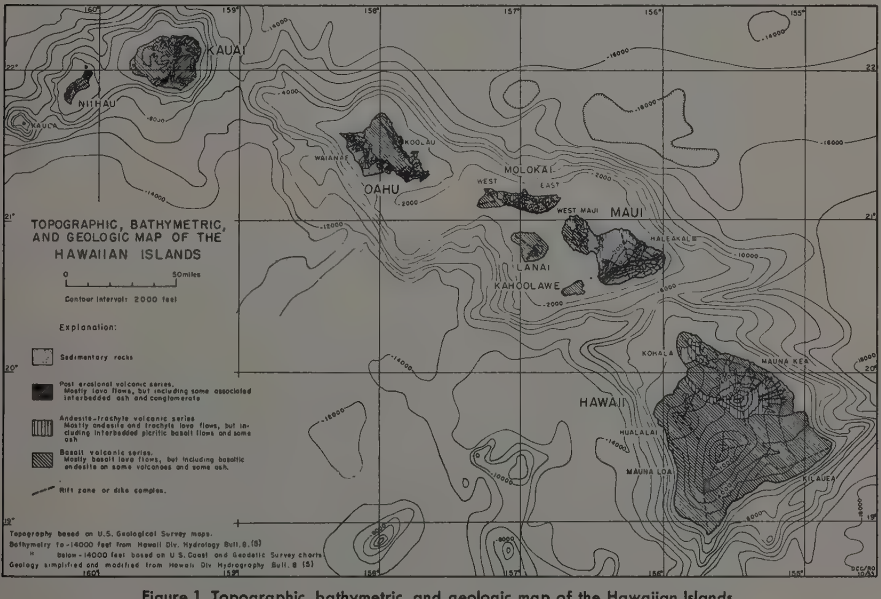


Figure 1. Topographic, bathymetric, and geologic map of the Hawaiian Islands.

[1] Senior Geologist, Experiment Station, HSPA.

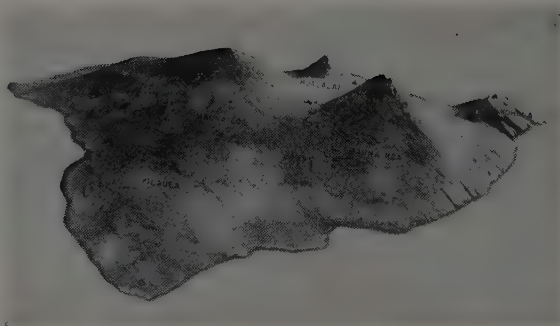


Figure 2. The island of Hawaii from the northeast. Hawaii is composed of the domes of five volcanoes. Contrast the smooth slopes of Kilauea and Mauna Loa, which are still active, with the rugged topography of Kauai shown in Figure 8. (Photograph of a relief model at the University of Hawaii.)

Each dome is composed, in the largest part, of thousands of basaltic lava flows of the kind that are still being erupted every few years by Mauna Loa and Kilauea. These flows are highly porous and pervious, being filled with cracks, gas cavities, lava tubes, and clinker beds. The lava erupts through fissures or rifts which generally follow well-defined axial or tri-axial zones of fundamental weakness in the volcanic domes, as illustrated in Figure 3. When the eruptions end, the rifts become plugged by lava and form steep sheet-like masses called dikes that are composed of rock much more compact than the flows through which they cut. (Figure 4) In places, offshoots from the dikes follow the bedding of the flows. These are called sills.

Centrally on the volcano there may be developed collapse depressions, or caldera, like Mokuaweoweo on Mauna Loa, which are repeatedly filled and reformed by new collapses. (Figure 5) The flows ponded in calderas are thicker and more compact than those on the flanks of the volcanoes.

Figure 3. Lava is flowing away to the left of the fissure from which Mauna Loa erupted in 1949. (Official photograph, U. S. Navy)

Figure 4. A dike cutting thin-bedded lava flows, exposed in the lower part of Waimea Valley, Kauai. Note the much greater porosity of the lava flows. The dike is about 2 feet thick.

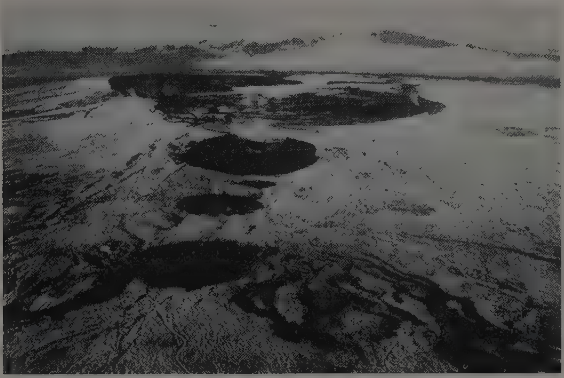


Figure 5. Mokuaweoweo caldera on the summit of Mauna Loa, Hawaii, with similar but smaller pit craters in the foreground. (U. S. Army Air Force photograph)

Figure 6. A bed of volcanic ash several feet thick, exposed in Hanapepe Valley, Kauai.

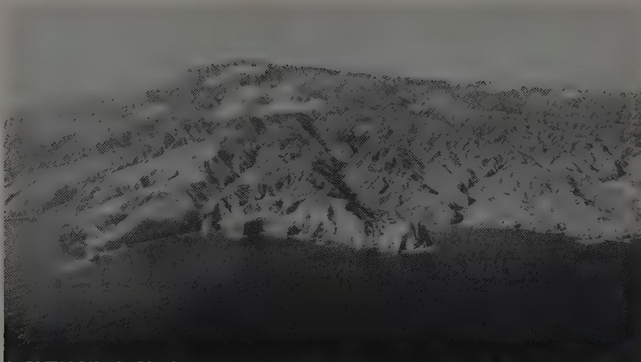


Figure 7. West Maui from the north. Puu Koae, the conspicuous headland to the right of center, is a bulbous dome of trachyte. Thick trachyte and andesite flows crop out in the sea cliffs left of Puu Koae and make the smooth land surfaces inland. (U. S. Geological Survey photograph)

The cinder cones, formed by gas-induced fountaining at the eruptive vents, comprise a very small part of either the volume or the area of the whole volcanic domes; but the finer material called ash may be scattered widely, and if accumulated at one horizon from many eruptions before being buried by flows, it may form extensive sheets of material less pervious than the flows. (Figure 6) Mauna Loa and Kilauea are still actively engaged in building primitive basalt domes; Lanai and West Molokai are similar domes, long inactive.

Other Hawaiian volcanoes represent domes which are basically and originally similar, but which have added later complexities. Owing to differentiation of lavas deep in the earth, there has come a stage in the development of several of the Hawaiian volcanoes when the primitive basalt dome receives an overlay of flows of more siliceous lava, called andesite, sometimes interbedded with flows of picritic basalt lava less siliceous than the primitive basalt. The andesitic lavas, especially, are more viscous than the primitive basalt lavas. The andesite flows are consequently thicker and more massive, and they make a less pervious sheath over the very pervious core of basalt flows. Mauna Kea, Kohala, and Hualalai have such a sheath or veneer of andesite flows. If they ever had calderas, these have been filled up and obliterated by the andesite flows. Hualalai and Kohala have, in fact, erupted trachyte lavas even more siliceous and more viscous than the andesites, making what are called bulbous domes at the vents and tremendously thick flows, as shown in Figure 7.

The Niihau, Kauai, Waianae, East Molokai, Kahoolawe, West Maui, and Haleakala volcanoes have also passed through an andesite or trachyte stage.

The frequency of eruptions is so great during the basalt stage that weathering produces few soils except on the rapidly broken-down ash beds. Since the frequency drops off in the andesite stage, soils may be formed and some valleys carved. But toward the end of, or after, the andesite stage, there has come a stage in the history of this last named group of volcanoes during which weathering and erosion are uninterrupted and great valleys are carved, many of them originally much deeper than they are now. The Koolau volcano of Oahu has also passed

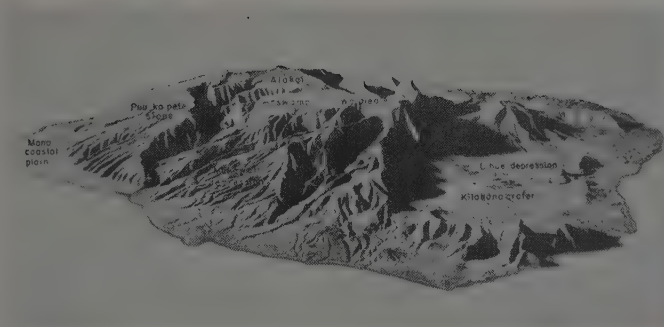


Figure 8. The island of Kauai from the south. The rugged topography is the result of erosion and faulting of the original basalt dome. Post-erosional flows underlie most of the flatter topography in the foreground and at the right. (Photograph of a relief model at the University of Hawaii)

through such an erosional stage, though it was not previously veneered with andesite. The effects of erosion have been guided and heightened on some of the volcanoes by faulting, that is, by actual displacement of parts of the domes.

The beginning of extensive erosion does not mark the end of volcanism, however, because on each of this group of volcanoes there have been sporadic post-erosional eruptions, of very minor extent on the Waianae and Kahoolawe volcanoes, but partially filling the deep valleys and greatly extending the shores of Kauai and the Koolau volcano of Oahu, and making well-known cones like Diamond Head on Oahu and Kilohana on Kauai. (Figures 8 and 9) The post-erosional lavas include basalts again and also rocks more deficient in silica. The porosity and permeability of these late lavas are highly variable and, as a bulk, very much lower than that of the original basalts, because the eroded nature of the topography over which they were erupted created numerous situations where the flows ponded, interbedded conglomerates resulted from the blocking of drainage by the flows, and a high proportion of associated ash beds were formed.

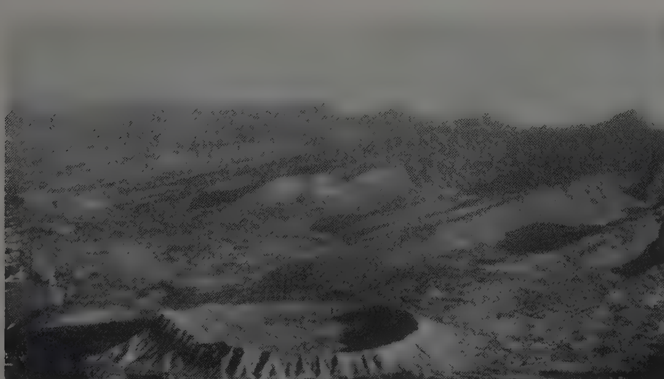


Figure 9. Diamond Head, Honolulu, and the Koolau Range of Oahu. The Koolau Range is an eroded basalt dome. Diamond Head is a post-erosional cone. The flat part of Honolulu, on the left of Diamond Head, is built on a coastal plain.

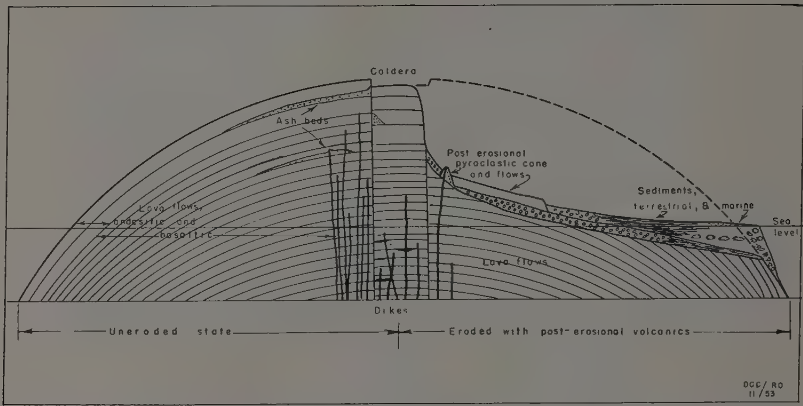


Figure 10. Diagrammatic cross section of an idealized Hawaiian volcanic dome showing geologic structure.

Concomitant with the erosion, there has, of course, been sedimentation, creating around the eroded volcanoes coastal plains, composed of both alluvium brought down by the streams and of calcareous sediments consisting of coral reefs and sand derived from the coral and shells. The coral reefs are highly pervious, but the alluvium is, in general, much less pervious than the basalt lava flows. Owing to glacial and other shifts of sea level, valleys cut at one time far below present sea level have been first drowned and since filled with sediments, and former coral reefs and beaches have been stranded above the present shores.

The geologic structure resulting from this typical history of a Hawaiian volcanic island is shown in Figure 10.

The ultimate fate of the major Hawaiian Islands will be erosional reduction to shoals and coral atolls like the leeward islands of the Hawaiian Archipelago.

Rainfall

The fact that the Hawaiian Islands are still high, ranging up to nearly 14,000 feet elevation above sea level, is of great importance to their climatology (2). The rainfall at sea, in the Hawaiian semi-tropic situation, is somewhere between 15 and 30 inches per year, perhaps enough to grow pineapple but certainly not enough to support a sugar plantation of Hawaiian productivity. This sea rainfall consists partly of frequent light showers from the trade winds, and partly of sporadic heavy falls during storms. Like the winds themselves, the two types of rains have seasonally variable frequencies, the light trade showers dominating in summer, the heavy rains dominating in winter.

The Hawaiian volcanoes are, fortunately, high enough to disturb significantly the flow of a part of the layer of moisture-laden air associated with both types of winds; the higher ones, in fact, penetrate the moist layer completely during trade wind periods when the layer is only 6000 to 7000 feet thick. The winds are diverted up and around the volcanoes, in the process cooling and losing their moisture-holding capacity and thus producing rain. During trade-wind weather, the high-rainfall areas on the ground beneath are belts at an altitude of about 3000 feet

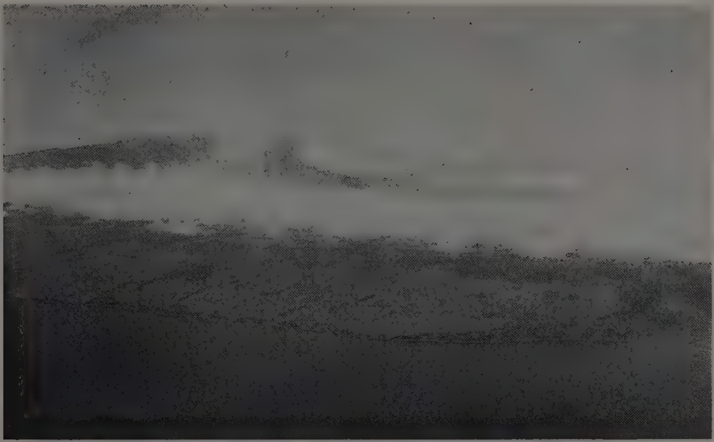


Figure 11. The trade-wind cloud bank on the windward side of Mauna Kea, Hawaii. An area of maximum rainfall lies on the flank of the mountain under these clouds.

on the windward side of the mountains high enough to penetrate the whole moist layer (Figure 11), and areas concentrated near the tops of the lower mountains. (Figure 12) Mean annual rainfalls range to a maximum of more than 400 inches in these areas. On the leeward sides of the volcanoes, trade-wind rainfall may be reduced below the sea rainfall rate, because the windward sides, or summits, have robbed the winds of their moisture. The resulting pattern of annual rainfall is shown in Figure 13.

This so-called orographic effect has long been recognized in trade-wind rainfall distribution. Recent work (3) suggests that it is also very important in explaining some complexities in seasonal distribution of storm rainfall as shown in Figure 14. The rainfall at low leeward stations that receive little trade-wind rain, is, of

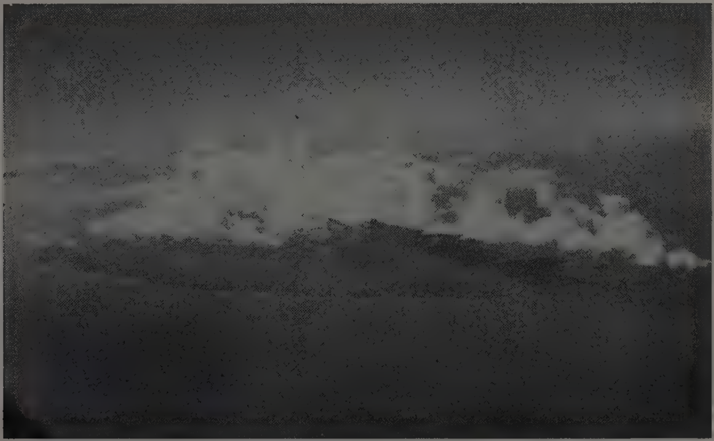
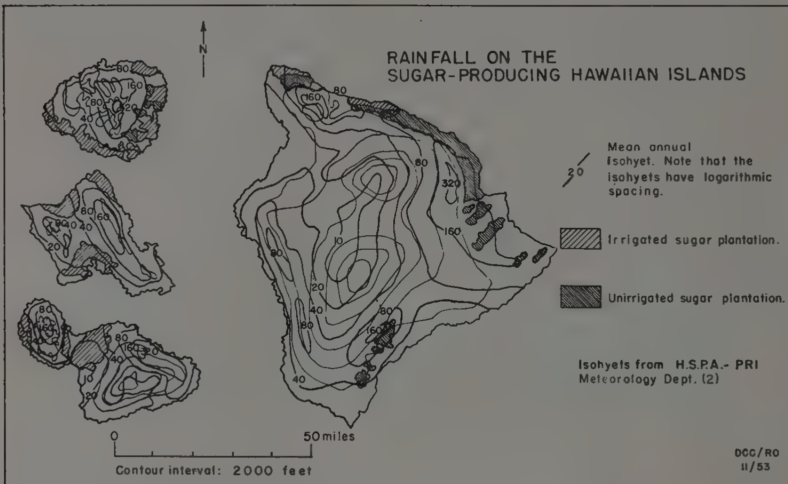


Figure 12. The trade-wind cloud bank over the summit of Lanai. An area of maximum rainfall lies at the summit of the mountain



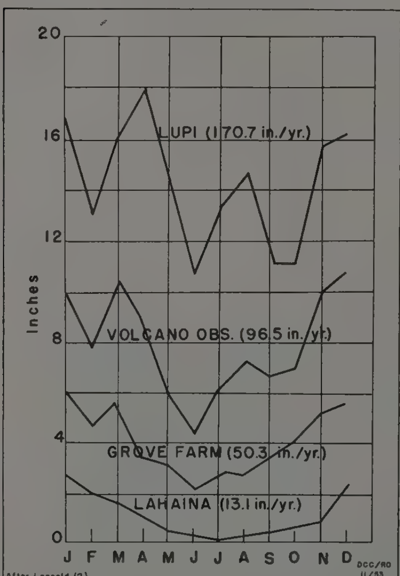


Figure 13. (Top) Map showing rainfall on the sugar-producing Hawaiian Islands.

Figure 14. (Below) Seasonal distribution of rainfall at typical stations. (After Leopold)

course, dominated by storm rains with a winter maximum and summer minimum, as at Lahaina, Maui, for example. Even at moderately rainy windward stations, such as Grove Farm, Kauai, or the Volcano Observatory, Hawaii, the storm rainfall, increased by the orographic effect, still dominates the trade-wind rain. Only at high rainfall windward stations like Lupi, Maui, does the seasonal distribution of trade showers show up reinforced as much as the storm rains by the orographic effect, which, because of fundamental irregularities in the typical trade and storm

rainfall curves, produces not a single winter minimum, but three minima in February, June and October.

As should be expected, the short-term variability of rainfall at such stations is higher during the stormy winter season than during the summer season of steady trades.

One more rainfall effect of local importance is that induced by monsoonal circulation in areas leeward of the largest mountains, leading to maximum rainfall belts like that at Kona, Hawaii.

HYDROLOGY AND WATER DEVELOPMENT

Whether or not irrigation is necessary to supplement rainfall for sugar cane culture depends not only on the annual rainfall rate but on the seasonal, and longer term, variability in rainfall, combined with the temperature and with the nature of the soil. Because there is some correlation between annual rainfall and these other factors, it is customary to regard the minimum mean annual rainfall for unirrigated cane growth as somewhere between 60 and 80 inches. These mean annual rainfall limits include some allowance for annual rainfall variability, but during a dry year like 1953, areas with a mean rainfall of 60 inches lack sufficient rain for satisfactory cane growth. The maximum mean annual rainfall on lands in cane is 300 inches. In areas where the rainfall is so high, the growth is retarded due to the lack of sunlight and the lower temperatures.

On lands with less than 60 inches of natural rainfall a year, cane culture requires supplementation. It is the function of water development to make water available to these areas at the proper times.

One method of supplementation is, of course, the production of artificial rainfall. This method is under intensive study, and while the potentialities are inviting, considerable effort must still be devoted to fundamental research in cloud physics before rain-making becomes practical.

Another method is the desalinization of ocean water. This is feasible, but even with the latest processes, it is too expensive for irrigation purposes.

The only water practically available for irrigation is, therefore, the rainfall collected either from aboveground watersheds or from underground aquifers.

Evapotranspiration

Rainfall is subject to evaporation and transpiration losses before it can be developed. The estimates most often used for these losses are 30 inches per year for transpiration, and 20 per cent for evaporation. Past experiments have suggested that in the high-rainfall areas these estimates are much too high, both evaporation and transpiration being reduced in the high-humidity, low-temperature, cloudy environments. Experimental work on evapotranspiration in Hawaiian mountain areas is much needed for adequate evaluation of present and potential water supplies.

The water that escapes evapotranspiration is separated by the relative abilities of the soil to shed it or to absorb and transmit it into two fractions: runoff, which flows on or near the surface to streams; and infiltration, which sinks into the rock. The relative proportions of infiltration and runoff vary tremendously from place to place. On much of the island of Hawaii where there are fresh lava

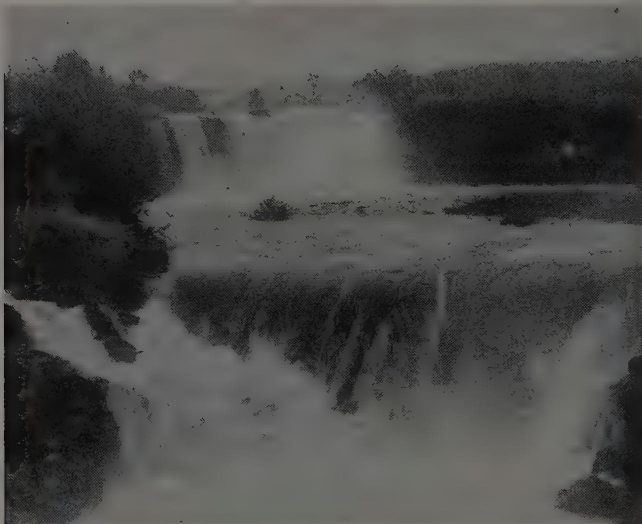


Figure 15. The Wailuku River near Hilo in flood. The low water flow is a minute fraction of that photographed.

flows at the surface, there is no runoff, even with maximum rainfall. No perennial streams reach the shore in 165 miles of Hawaii's 225-mile coastline, and not even mappable intermittent streams reach the shore in most of that distance. In contrast, the runoff from the Alakai Swamp on Kauai, which overlies massive, dense, caldera-filling flows, probably very greatly exceeds the infiltration.

Runoff

The runoff is the most direct source of surface stream water (1). Because its path is so direct, however, it is in general the least useful. Most Hawaiian streams are notably flashy. (Figure 15) Bank storage in streams does to some extent stabilize the flow of the streams. The longer and flatter the stream, the greater the stabilizing effect. The longest stream channel in the Islands is one about 25 miles long on the east slope of Mauna Kea. Its grade is so steep that after a rain, most of the runoff in its watershed drains to the sea within a few hours, and the last remnant sinks into the permeable ground, leaving the channel dry except for spring flow in the lower section. Many more streams on all the steep flanks of the volcanic domes are completely dry most of the time. The lower courses of major streams on the deeply-eroded volcanoes are very flat, so that bank storage per unit length is greater; but the length of these flat stretches is only a few miles at the most, so that the total effects are again small. Forest vegetation in the high rainfall areas retards runoff before it reaches the streams, a matter of importance in controlling erosion, but only very flat swampy areas offer enough storage to stabilize the runoff significantly.

The amount of time during which the discharge of various Hawaiian streams equals or exceeds various percentages of the mean discharge of the streams is

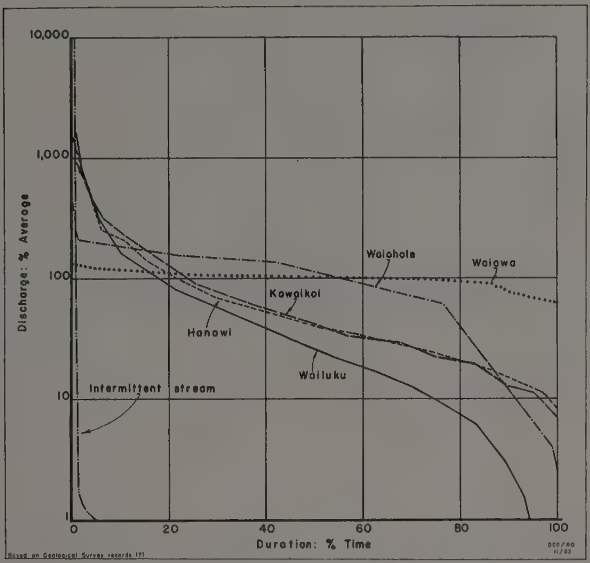


Figure 16. Duration-discharge curves for typical streams.

shown in Figure 16. (7) The duration-discharge relation for a typical intermittent stream on one of the volcanic flanks is estimated. The likelihood of the utilization of such streams is so remote that they are not gauged. The flow of the Wailuku River on Hawaii is dominated by surface runoff from a high-rainfall area of comparatively little variability. The runoff is also supplemented by spring flow, but even so, it drops to a small fraction of the mean flow during much of the time. The flow of Kawaikoi Stream on Kauai is entirely runoff. Its comparative stability is the result of comparatively constant yearly rainfall and natural storage in the Alakai Swamp. Most Hawaiian streams would be of small value without spring flow, whose origin will now be discussed.

Infiltration and Ground Water

In general, the pervious rocks above sea level are unsaturated with water. Water infiltrating them finds its way nearly vertically downward until it meets a saturated zone, some body where some of the ground water (4) (6) is prevented or restricted by some rock structure or by salt water, as shown diagrammatically in Figure 17. Ash, soil, or alluvium are commonly sufficiently impervious to restrict downward movement of water percolating through the lava flows with which they are interbedded, resulting in the accumulation on them of what are called perched bodies of water. Locally, massive sections of the lava perch important bodies of water. Sills, which are offshoots from dikes that follow the bedding, may also perch water. The perching members, or impervious beds, having once been at the ground surface, or having followed what was once the surface, have slopes characteristic of the surface, and just as the rain water that once fell on some of them concentrated in low channels and ran off in streams,

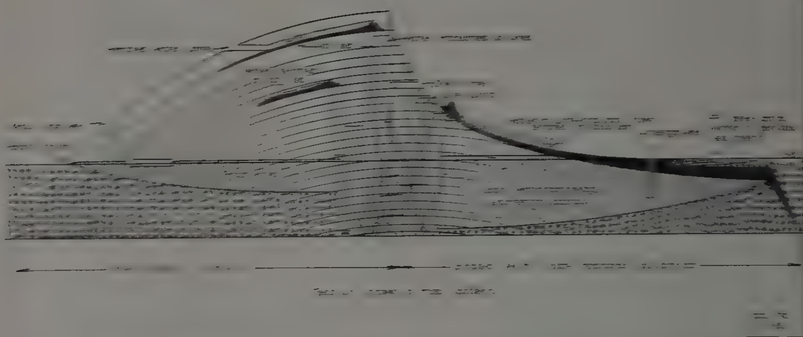


Figure [illegible]. Diagrammatic cross section of an idealized Hawaiian volcanic dome showing occurrence and development of ground water.

[illegible] the flows from these perched bodies are much more stable [illegible] down to some deeper body [illegible] been exposed by ero- [illegible] surface, forming springs [illegible] that provide the permanence of

Figure [illegible]. A perched spring: the [illegible] Spring, Maui. U. S. Geological Survey photograph.

Figure 19. A dike spring: Waihee Spring, Oahu. The dike is on the right. (U. S. Geological Survey photograph)

flow of many Hawaiian streams, such as the Hanawai Stream on Maui, whose duration-discharge curve is shown in Figure 16.

Perched springs do not generally have so uniform a flow as springs of another class. The rift zones of the volcanoes, as already discussed, are filled with dikes, making what is called a dike complex, in which the pervious lava-flow rock is separated into a great number of compartments. The dikes in most dike complexes are sub-parallel, and intersect both horizontally and vertically. Water infiltrating to the dike complex is retained in these compartments, filling them until the dikes are overflowed either underground or on the surface, or until the pressure at leaks through the dikes is so great that the leakage balances the infiltration. Where valleys have been eroded into the dike complexes of the older volcanoes and have cut through dikes impounding water, springs have resulted, whose stability of flow is very great because of the large amount of variable storage in the dike compartments as compared with the flow through them. (Figure 19)

Figure 20. A basal spring at Kaupo, Maui, representing discharge from a Ghyben-Herzberg lens.

The Waiahole Stream, whose duration-discharge curve is shown in Figure 16, is fed by dike springs.

The underground leakage from perched water bodies and dike compartments, and the infiltration from areas not underlain by perching members and dikes, percolate down nearly to sea level to accumulate there as bodies of fresh water floating in the rocks on sea water. These are called Ghyben-Herzberg bodies after the men who first discovered the nature of their occurrence. The density of fresh water is about one-fortieth less than that of sea water. As a consequence, the fresh-water bodies float with their lower surfaces, the contacts between fresh and salt water, about 40 times as far below sea level as their upper surfaces, the water tables, stand above sea level. Where the rock is pervious to the shoreline, the outflows from these bodies form shoreline springs. (Figure 20) The water table must slope seaward to induce the seaward flow, and the salt-fresh contact must rise seaward at a rate 40 times as great. To compensate for the seaward decrease in cross-sectional area, the slope must increase seaward, and the salt-fresh contact must rise even more rapidly so that these basal bodies of fresh water have a lenticular form. Where there are coastal plains underlain by sediments whose permeability in bulk is very low compared with that of the bedrock lavas, the normal seaward outlet is blocked off. The water must back up higher and deeper in the bedrock until it can escape either in springs over the sedimentary cap or in deep submarine springs under the sedimentary cap, or until the pressure on leaks through the cap is sufficiently high to make the leakage balance the inflow. The Waiawa Springs on Oahu, whose duration-discharge curve is shown in Figure 16, represent outflow from the Pearl Harbor basal lens at a point where the caprock is low. On the Maui Isthmus, where there is no caprock, the head or altitude of the water table increases mountainward, so that at a point three miles from the coast it amounts to about five feet, and the fresh water lens is about 200 feet thick. In contrast, back of the caprock in Honolulu, there was an original head of over 40 feet and an original thickness of over 1600 feet of fresh water. This 40-foot head was, and even the present 20 or 25-foot head is, higher than the surface of the lower part of the coastal plain, so that artesian conditions exist under the Honolulu coastal plain; that is, the pressure is sufficient to raise the water above the aquifer, the water-bearing rocks and, in fact, above the surface of the ground. Such artesian conditions are common wherever there are coastal plains around the margin of the deeply-eroded volcanoes.

The lower surface of a Ghyben-Herzberg lens is not actually a sharp contact but, because of diffusion and mixing, a gradational zone.

There are modes of occurrence of ground water in Hawaii other than those discussed; such as, water confined by unconformities, water impounded by stray dikes and perched artesian water. The modes discussed are, however, the most important.

Surface-Water Development

Water available for irrigation supplies may thus be found in both surface streams and ground-water bodies. About 400 billion gallons of water are used annually for sugar cane irrigation, approximately half of which is surface water.

Surface-water development can be successful only when combined with storage, either natural or artificial, or both. The minimum artificial storage is required

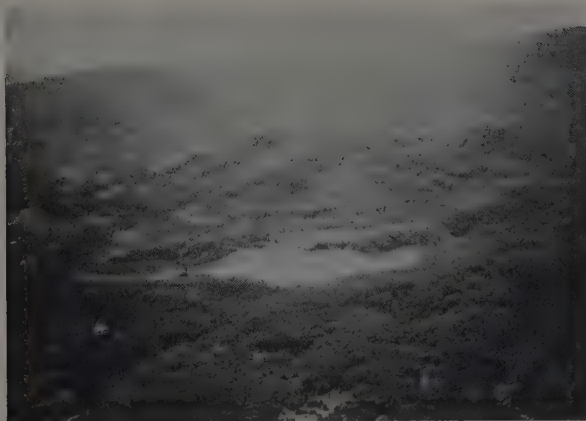


Figure 21. The Alexander Reservoir on Kauai. Sites suitable for reservoirs as large as this, which holds nearly a billion gallons, require unusual geologic and topographic situations.

in developing streams of small variability, those fed by springs representing the discharge of ground-water bodies with large storage, such as in dike compartments, or those fed by swamps or springs with smaller storages but in areas of higher and more uniform rainfall. The artificial storage required may be of two different orders of magnitude. Because of manpower considerations, irrigation is not generally continuous, but is stopped at night and over weekends. The most efficient use of a constant supply of water requires small reservoirs in which water can be stored for these periods, with a consequent increase in irrigation rates when the irrigation is actually practiced. This short-term storage is necessary with any kind of development. Seasonal storage requires much larger storage capacities. Stream flow is seasonally variable, with the minima coming commonly just when the rainfall is lowest and the irrigation demand is highest. Minimum stream flows are in this case the only useful ones unless seasonal storage can be provided. Irrigation demands run in units of several million gallons per day. Seasonal storage thus involves capacities of several hundred million gallons.

Because of the steepness of stream gradients and the generally high permeability of the ground, suitable reservoir sites, particularly large ones, are uncommon. The two-billion-gallon Wahiawa Reservoir on Oahu is successful because it is in a comparatively level valley which still reflects the flattening of the Koolau Volcano flows where they ponded against the Waianae volcano, and because the rainfall is sufficiently high to have induced deep weathering, while erosion has not kept pace because of the flatness of the slope. The two-billion-gallon Koloa reservoir on Kauai lies over a former swamp underlain by tight alluvium deposited against a late lava flow. The one-billion-gallon Alexander reservoir on Kauai lies in a natural basin formed by post-erosional cones and flows in a rainy and deeply-weathered area. (Figure 21) Somewhat smaller reservoirs on McBryde and Lihue plantations on Kauai have been constructed in deeply-weathered, ponded, post-erosional lavas.

The stream diversions themselves, though generally minor parts of the whole surface-water development so far as expense is concerned, can be tricky because

Figure 22. The Wainiha Intake on Kauai. Water from the Wainiha River is carried through 4 miles of tunnels for hydroelectric power development.

they must bypass freshets in such a way that the intakes are kept as clear as possible of gravel, and as much as possible of the low flow of the streams is retained. (Figure 22)

The transportation involved in surface development should be considered in two parts, one horizontal, one vertical. The natural tendency of water to move downward, whether on the surface or underground, puts a premium on water development at high levels, which obviates the necessity for pumping. Surface-water development is usually high-level development, the height representing a balance between the increase in length of horizontal transportation required with added elevation, the reduction in stream flow with added elevation, and the premium for

Figure 23. The Lowrie Ditch on Maui, one unit of the 30-mile East Maui ditch system, carries up to 350 million gallons per day to irrigate cane on the Maui Isthmus. (Photograph, HC&S Co. Breeze)

Figure 24. A flume and tunnel on the Wailoa Ditch, another unit of the East Maui ditch system. (Photograph, HC&S Co. Breeze)

added elevation of delivery. On one hand, the Kokee ditch of Kekaha Sugar Company on Kauai picks up water at an altitude of 3000 feet and more, and delivers it to cane fields at as much as 2500 feet altitude. On the other hand, McBryde Sugar Company, also on Kauai, pumps Hanapepe river water from almost sea level to 375 feet altitude; and basal springs, representing leakage from Ghyben-Herzberg lenses, are pumped for irrigation by Kahuku and Oahu Sugar Company.

The longest ditch system is that of East Maui that brings water 30 miles around Haleakala from the wet northeast side to the H C & S plantation on the west side. (Figure 23) The system includes several ditches with a combined capacity of 350 million gallons per day. Much of this system, as well as other so-called ditch systems, is actually a series of tunnels which, besides shortening the route in rough country, reduces some of the difficulties caused by landslides. (Figure 24) The longest transportation tunnel, the Waiahole tunnel, three miles long, brings water through the Koolau Range from the north side for irrigation of Oahu Sugar Company's fields. In areas of post-erosional volcanoes and other tight rocks, lining of ditches and tunnels is not required. In flank flows, however, lining is essential to reduce leakage. Flumes and siphons are also used. Pipelines are necessary, of course, to transport pumped water. The major surface water developments are shown with major streams in Figure 25.

Ground-Water Development

As already shown, ground-water discharge is important even in most surface-water development. It can be made more important by artificial development, as

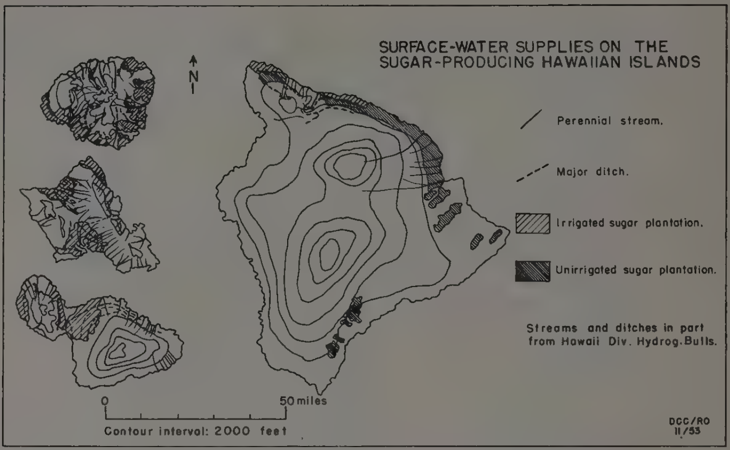


Figure 25. Map showing surface-water supplies on the sugar-producing Hawaiian Islands.

indicated diagrammatically in Figure 17. For example, perched water, naturally leaking underground or discharging to the surface at too low a level to be included in a given ditch system, can be recovered artificially by tunnelling along the upper surface of the perching member and tapping the underground streams flowing in underground valleys in a manner quite analogous to the diversion of surface streams in surface valleys. (Figure 26) If the perching member is leaky, it should be possible to recover more water by tunnel development than originally appeared in springs. Actual experience, where measurements are adequate, suggests that more often than not, the total flow is not greatly increased. Development of perched water cannot usually add to storage or stability of flow. The advantages

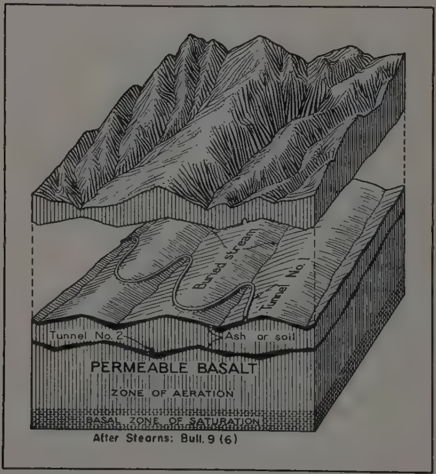


Figure 26. Block diagram illustrating the manner in which tunnels tap perched water from buried ash beds.

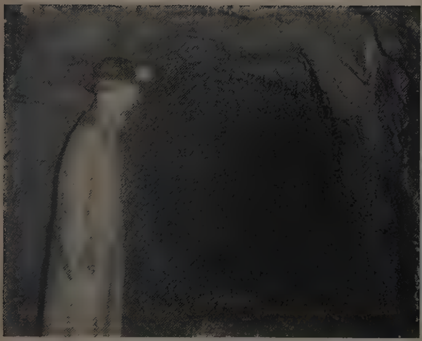


Figure 27. The Iao Tunnel on Maui. This tunnel is nearly 5000 feet long and cuts 150 dikes. At this point, water pours in from the top as well as from the bottom and sides. Note the dike at the left of the man.

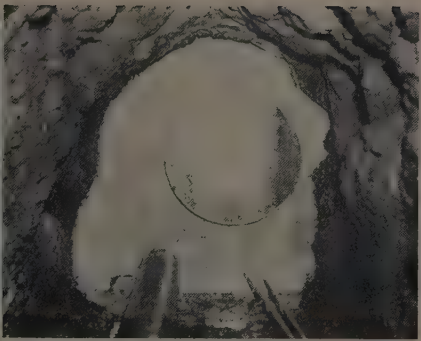


Figure 28. A concrete bulkhead in a dike in the Manoa tunnel on Oahu. Water can be stored behind the bulkheaded dike just as it was before the dike was punctured. (Photograph, Honolulu Board of Water Supply)

of development lie in the concentration of discharge at points advantageous from the transportation standpoint.

Ground-water bodies in dike complexes can also be developed artificially by tunnelling. (Figure 27) Tunnels, penetrating dikes below the level of original dike springs, drain down the dike compartments, resulting in the release from storage of very great quantities of water. The drainage may persist for years after the tunnels are completed. If the dikes are leaky, the final stable flow recovered by tunnels should be greater than the original spring flows by the amount of reduction in leakage brought about by lower pressures resulting from the lowered water tables. Again, however, experience with the few dike tunnels where there have been adequate measurements of spring flow before and after tunnelling, is that the developed flow is little or no greater than the original spring flow. This does not indicate a total failure of tunnelling. On the contrary, it indicates a tightness of the dikes that can be capitalized on by the construction of bulkheads, which seal the dikes again and recreate underground reservoirs of much greater tightness than any available on the surface. (Figure 28) Such reservoirs can be drawn on when water is required, and be allowed to fill by natural recharge when water is not required. Dike compartments may also be developed by drilling wells. In this case, the natural storage is utilized to the utmost, but pumping is required to get the water to the surface.

The flows of perched-water tunnels are usually small; few exceed a million gallons per day, though some are several thousand feet long. The flows of dike tunnels commonly run to several million gallons per day. The longest dike tunnel, that in Iao Valley on Maui, is nearly 5000 feet long. Existing dike tunnels are all remote from plantation areas, because the dike complexes are never exposed except by the deep erosion that produces rugged terrain unsuitable for agriculture. The perched-water bodies of largest flow are also remote from irrigated areas, because they occur in high rainfall areas. But developments of these types of water share the advantage of high level. Together with high-level stream diversion, they offer the opportunity of getting water to high areas of cane without the necessity of pumping.

Figure 29. An artesian well at Kaunalewa, Kauai. Water from this and other artesian wells collects in a sump from which it is pumped for irrigation. Pump suctions may also be connected directly to well casings.

Basal-water development, that is, development from the Ghyben-Herzberg lenses, has the advantage of supplying large quantities of water in plantation areas. In the lowest cane lands on coastal plains underlain by artesian sections of the Ghyben-Herzberg lenses, wells may be drilled that will flow without pumping. (Figure 29) Most basal water must, however, be pumped for delivery to the cane fields. Water in the thick basal lenses, confined by sedimentary caps, can be developed by vertical wells drilled with the time-honored churn drill, or by the newer rotary drill. Depending on the permeability, the drawdown created, and their size and depth, such wells may yield anything up to five million gallons per day. When drilled at low altitudes, several may be manifolded for draft with a single pump. At higher altitudes, they must be either equipped with individual deep well pumps, or manifolded in a pit or tunnel and pumped from a pumproom not far above the water table. Yields up to 15 or 20 million gallons per day have been procured from batteries of drilled wells. The deepest wells for cane irrigation will probably be at Lawai, Kauai, where wells will shortly be started from 450 feet altitude, will meet the water table at about 60 feet altitude, and will probably be carried to a total depth of 750 feet, 300 feet below sea level. Some old wells still used for irrigation extend 700 feet below sea level. Deeper ones once existed, but they became salty when the storage in the lens was reduced and the zone of salt mixture rose.

Vertical drilled wells have limited utility in the thin, unconfined, Ghyben-Herzberg lenses because they penetrate to brackish or salt water before their capacity can be very high. For draft of water from such lenses, the Maui-type well was developed. (Figure 30) This is essentially a tunnel skimming off the freshest part of the water in the lens with a sump and pumproom connected with the surface by a pit or shaft as shown in Figure 31. Vertical shafts are generally most economical, but there is so often an advantage in having the shaft reach some permeable zone which involves a horizontal as well as a vertical component, that 30° inclines are very common. The deepest Maui-type shaft is the 550-foot

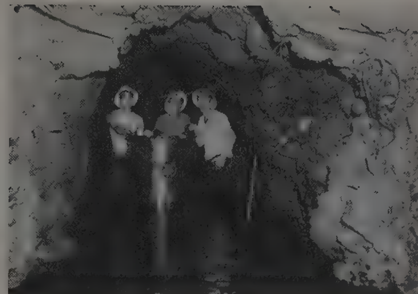


Figure 30. Infiltration tunnel of a Maui-type well at Puunene, Maui. (Photograph, HC&S Co. Breeze)

Kekaha shaft of the Hawaiian Commercial and Sugar Company. Depending on the capacity required, the permissible drawdown, and the permeability, tunnel lengths may range from mere stubs to several thousand feet. All but the shorter systems generally consist of more than one tunnel. Capacities range up to the 40 million gallons per day capacity of H C & S pump 7, which, by the way, has less than 600 feet of tunnel. The tunnels may be driven at the water table or as much as 30 feet below it. The greater depths have the advantage of permitting a higher drawdown and greater yield per unit length where the thickness of the lens is sufficient to permit it. Their construction requires auxiliary pumping for dewatering.

The Ghyben-Herzberg lenses have very large storage capacities, so that no surface seasonal storage facilities are required in conjunction with their development. They are pumped when the water is required, and permitted to recharge when the water is not required. Even short-term storage is sometimes omitted.

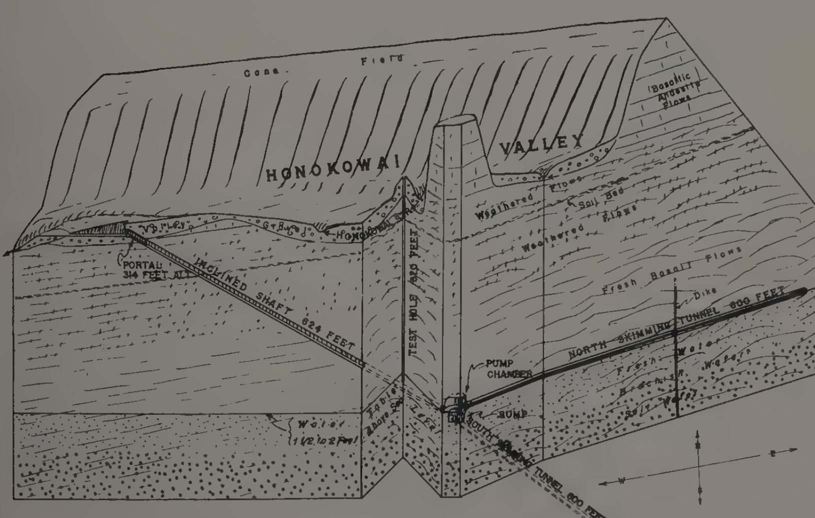


Figure 31. Block diagram of the Honokowai well, Maui, a typical Maui-type well.

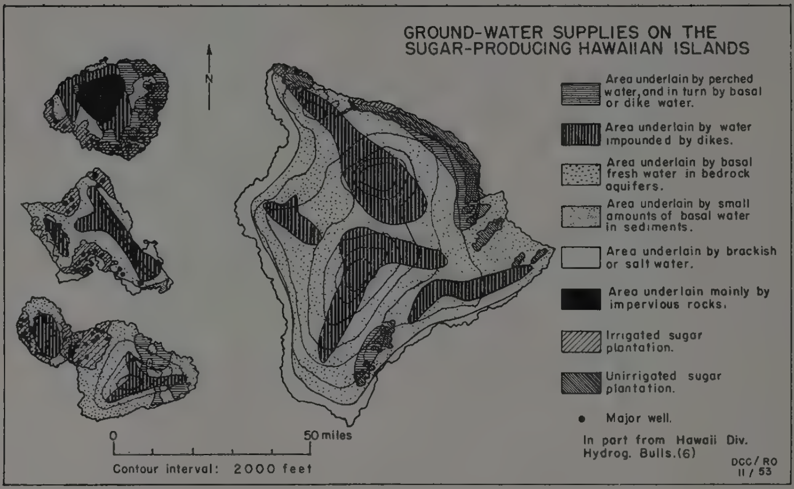


Figure 32. Map showing ground-water supplies on the sugar-producing Hawaiian Islands.

The major wells are shown in relation to general ground-water conditions in Figure 32.

Artificial Recharge

The water of lowest value in or on the ground is freshet surface water because possibilities of surface storage are limited. The highest storage capacities are in natural ground-water reservoirs. The artificial introduction of surface water into the ground-water reservoirs has thus a high potential value. To some extent, such artificial recharge has already been practiced. For many years, when it was not being pumped for irrigation, Hanapepe river water on Kauai has been run into Maui-type wells in the valley. For a couple of years, water from the East Maui ditch country has been transported to the Maui Isthmus, even when not needed for irrigation, for release at points from which it can percolate to the basal lens. Artificial recharge is certain to find wider utility in the future.

SUMMARY

To summarize, there is a wide geographic variation in rainfall in Hawaii. Some areas otherwise suitable for agriculture are too wet and have too little sunlight for economical cane growth. Others, somewhat drier and sunnier, have sufficient rainfall for cane growth. The best areas, so far as sunlight is concerned, have too little rain for cane growth. It is one of the functions of water development to transport water for irrigation from areas of surplus to areas of deficiency. This may involve either diversion of surface or ground water in or close to areas of high rainfall and a comparatively long path of artificial transportation, or the utilization of ground-water movement for most of the transportation, with diver-

sion in the plantation areas. A second function is the storage of water so that deliveries may be uniform or, preferably, may be variable inversely with the rainfall variation. A part or all of this storage may be provided naturally by ground-water bodies or swamps. It may be supplemented artificially by surface storage or by artificial recharge of ground-water bodies.

In no lands of the earth are areas of such divergent climate placed in closer juxtaposition than in Hawaii, and in no land even remotely similar has a more highly developed technology of water development been evolved.

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ECONOMICS OF WATER DEVELOPMENT

Joel B. Cox[1]

Both engineering and irrigation make economic applications of data from many branches of science. In both fields, the accuracy and completeness of the solution to economic problems are of equal importance with the technical emphasis placed on problems of design and method. The economics of water development presents a clear-cut example of engineering economics within the framework of the larger field of irrigation economics of which it is a part. As in all problems of engineering economics, the statement of the problem for any particular application may be made simply and clearly. For any proposed development, the cost of service must be accurately computed, and the value of the service rendered. In every case involving new capital investment, the proposed plan will be in competition with many other demands for capital investment in the industry. It is not enough to know that a proposed plan will pay a fair return on the capital employed—it must pay a higher rate of return on investment than will the other available opportunities, such as, in the sugar industry, mill improvements, harvesting and transportation equipment, roads, buildings and all the essential elements of the productive plant required for a sugar plantation.

The economics of water development constitutes a section of the broader field of the economics of irrigation which, in turn, is an element in the exceedingly broad and comprehensive field of regional planning which serves to outline and develop the optimum use of both the land and water resources of an entire region. Within this broader field, any development of irrigation should be considered from such standpoints as: the effect on employment and general or total income to the Territory; the effect on the revenue of the government of the Territory and its political subdivisions through water rents and tax revenue of every kind; the choice of the highest and best use of both water supply and land, with the highest values for water supply going to such purposes as domestic supply; and the determination of the political and social advantages for such alternate use of irrigation water as for diversified agriculture as compared to a single crop, such as sugar cane. The utilization and development of hydroelectric power, either as a competitive use or as a joint use of the same water, is frequently involved. Changes in the irrigation of arable land will often have important and highly valued effects on the general hydrology of an area involving, as they may, exhaustion of underground basins through increases of pumping, or recharge of such basins from percolating waters not transpired by the cane. In some cases, there will be conflicting demands for watershed areas. Development of water must be considered, bearing in mind the interrelationship between forest cover, runoff and

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infiltration with such competing or supplementary uses as pasture, residential areas or recreational areas. These factors are not our topic for the day, but are essential background for our thinking. In the wider field of economics, they will generally be made effective upon the specific problems of the limited field of water development by a single corporation in one of two ways: first, limitation on such private development will be enforced through some form of government action, such as special or differential taxation, an example of which is the present exemption of forested watersheds from real property taxation when they are placed under the control of the Board of Agriculture and Forestry, or through governmental regulation and control; or, second, limitation will be enforced more commonly through the operation of competition existing in auctions for water licenses. The high degree of competition for the use of land is evidenced by rental paid for the various uses; and the effect of competition for funds available for construction and improvements is evidenced through the operation of the stock market and of interest rates on borrowed capital.

If the effect of the wider economic pressures just discussed is understood, and if the necessary data from hydrology in its various branches, such as hydraulic engineering, scientific and experimental agriculture, industrial engineering and scientific management, is utilized, then any problem of water development becomes a straightforward application of the principles of engineering economics from the standpoint of the stockholders in a plantation corporation.

The process of solving any problem in the economics of water development consists in the following steps. First, there must be an exact outline of the present situation and of the various alternative forms in which improvement in this situation may be expected. It is very seldom that there is only one available means of effectuating an improvement in an irrigation water supply. Frequently, any such change in water supply must also be considered both with and without a change in the area irrigated. Each of the various available solutions must be analyzed, at least to the point where the best solution is clearly indicated. Next, for both the present condition and the proposed change, a complete cost and value equation must be developed, and it is the difference between the present and proposed financial result, the before and after picture, or, in other words, the marginal effect of a change in irrigation, which is to be ascertained. The evaluation of the cost factor in this economic equation lies particularly within the field of engineering. The technique for estimating or obtaining the necessary data and the technique for design are relatively well established. In most cases, a high degree of accuracy and precision may be expected in estimating the additional capital required for construction costs, the annual costs of operation and maintenance, and the return of the investment through the accumulation of depreciation reserves. Probably no elements will be involved in this work which require special attention here. It is, however, worthwhile to point out that the recent changes in the cost of construction, due to the decreased value of the dollar, have been very unequal in the hydraulic field. Certain elements, such as tunnel construction, have increased in a much greater ratio than the general average of construction costs. Others, especially unit costs of earth-dam construction, have increased much less and are, in fact, in some cases lower than they were some years ago. While machinery costs in general have increased rapidly, there have been notable improvements in efficiency, particularly in deep-well pumps. In

general, the cost of electric power for pumping has increased very slowly or, in some cases, not at all.

It is probable that estimates may be determined with a high degree of accuracy within the field of plantation operation, as, for example, the cost of applying a million gallons of water, the cost of additional fertilizer required or desirable for an increased tonnage of cane, the cost of harvesting and transporting increased tonnage, and the cost of milling increased tonnage. While our accounting systems will generally enable us to determine the average cost per ton of cane or per ton of sugar for the various elements of plantation cost, it is not always easy to determine how much such costs will be affected by the change in crop which a change in irrigation will produce. A great deal depends on the amount of change made and the length of time involved in such a change. In the event that the additional water is applied only to meet the requirements of an exceptional summer dry spell and that the net result is merely to hold a plantation's production to the expected level and not to increase it materially over a term of years, the plantation's overhead and indirect costs, even of irrigation and harvesting, are not affected, and the marginal value per ton of sugar is very high. If, however, the change in irrigation practice, year after year, will result in an appreciable increase in crop, nearly all of the overhead factors will be affected, though not necessarily increased directly in proportion to the increased production. At the other extreme, if the increase in irrigation water will place more land under cultivation and will require increased mill capacity, practically all the elements of plantation cost will be materially affected, and the net value per ton of sugar will be correspondingly reduced. It should be noted that the frequent practice of writing land leases with rentals determined by a percentage of the crop value severely penalizes water development.

Lying within another field of estimation which presents it own peculiar difficulties are the financial operations involved in converting sugar and molasses into cash and in channeling and subdividing this cash return into taxes, agent's commissions, HSPA dues, and other legal or customary demands which must be met before the earnings appear as net income. There are also the elements of a cost of money study as affected by the variability of income, the ratio of dividends to net earnings, the adjustment needed to provide a depreciation fund adequate for the replacement of all units of plantation construction and equipment in kind rather than for the recovery of their original cost. In such a time as we have experienced during the last 20 years, the element of continuing long-term inflation or drop in purchasing power of money has been a distinctly disturbing factor in all such computations. Even after suitable adjustments have been made to meet this situation and after what is believed to be a satisfactory and accurate computation is available showing the results at the present moment, the fact remains that our economic equation is concerned with similar financial formulas in the indefinite future. It is this element of prophecy in modifying the present-day picture to fit a reasonable forecast of the future of the industry which makes heavy demands on the skill and stable judgment both of the man preparing such estimates and of the Directors who review and act upon his recommendations.

I have kept until last that part of the problem which is probably of greatest interest to this audience. It is the part for which the accumulation of data is most needed, and it is perhaps the most technically difficult to interpret statistically.

This is the relationship between water applied as irrigation and the sugar produced from the irrigated field. Again, the concept is a simple one. If, under existing conditions, six million gallons of irrigation water per acre per crop are applied and a crop producing 12 tons sugar per acre is obtained, what crop will be produced if, say, 6.1 million gallons per acre per crop are applied, *all other conditions remaining unchanged?* The difficulties lie in the fact that water applied as irrigation is by no means the only independent variable affecting yields. Temperature, sunlight, rainfall, fertilization, time of year at which crop is started and harvested, ripening practice, soils, weed control and many other factors, play their important parts, and this complex of causes must be disentangled in order to measure accurately the separate marginal effect of irrigation. There are available two general statistical approaches to such a problem. Both must be carefully applied and checked, the one against the other. The first method is the controlled experiment, using Latin square arrangements for minimizing, and often eliminating, the effects of the other variables. You are all familiar, in your agricultural work, with the methods of design of such experiments and the statistical procedures which are available for their interpretation. The accumulation of results from such careful experimental work under a wide range of conditions is of first importance to the industry. The second method is the analysis and utilization of records of fields or other large areas for which the various factors are either relatively constant and uncorrelated with the irrigation applied, or are known. The data from such records may then be treated as a problem of multiple correlation, usually curvilinear rather than linear, and a significant relationship may be determined between the irrigation and the yield. This method has frequently been attempted with varying degrees of success.

In general, most plantations will have some useable data, so that comparison with the results at other plantations will give an estimate of the reliability of determination by this method. Again, the statistical procedures are well known, and the increasing availability of punched card records and IBM computing machines greatly facilitates the statistical procedure. The chief difficulty lies in the general lack of suitable experimental data to determine the form of the non-linear and time-influenced relationships, such as that between rainfall and yield and irrigation and yield. Suggestions and studies of this form are coming forward rapidly at the present time, and satisfactory forms for the computation may not be far away. Even the rough approximation of linear correlation will frequently lead to information which is indicative and of value, though it must always be regarded with some suspicion as obscuring or hiding the slope of the curve just where its determination is important. No variable of importance which is correlated with irrigation can be ignored, even though it has a satisfactorily even distribution through the data. For example, rainfall and irrigation applied are usually correlated. If the irrigation is from pumped water, it will be less when the rainfall on the fields is heavy. The correlation will be negative. If the irrigation is determined by the availability of natural flow in streams, it will be less during periods of low rainfall as the rainfall on the watershed is almost sure to be correlated with the rainfall on the fields. This correlation will be positive.

There are several types of problems which are commonly encountered. An increase in water supply may be made available at all times during the year, as from the flow of a steady spring; or the flow may be greater at times of heavy

rainfall, as from the unregulated flow of a stream; or it may be planned for use only at times of water shortage, as from a high-level pumped supply. An increase in the value of water or of a water supply through reservoir storage may be under consideration. A saving in water losses by such means as ditch lining may be considered. A reduction in the cost per million gallons of water may be achieved by a change in distribution ditches or in operating practices which decrease the average pumping head. There is also the important problem of the appraisal of water supplies or of water rights. Each problem is a special one, but for each the question is direct. What is the cost measured in dollars per year, and what are the benefits measured in the same terms? Is the net return on new or increased capital the best available for the plantation? The reliability and the precision of the answers to these questions will depend on the technical excellence of the experimental or observational technique furnishing the necessary data, and on the skill and resources shown in the statistical procedures which relate the measurements of sugar, growth of cane, millions of gallons of water, and dollars of earning and expenditure. But most important of all is a balanced and sound business judgment applied critically and impartially to each step in the process of appraisal. The technique of the promoter or propagandist is fatal to an orderly study or to sound conclusions. So is wishful thinking or the too early adoption of a desired solution. Until all the available facts have not only been disclosed, but studied and analyzed with complete open-mindedness, no decision can be sound.

SOME MOISTURE TENSION CHARACTERISTICS OF HAWAIIAN SOILS

A. H. Cornelison[1]

Moisture sorption curves on some 200 soils have been determined in the laboratories of the Experiment Station, HSPA, by the pressure chamber technique of Richards (3). Additional determinations on many other Hawaiian soils have been made by Waterhouse, Ewart and Thorne. This report covers only those soils which represent the principal soil types on the irrigated plantations.

The soil moisture energy concept as originally advanced by Buckingham in 1907 has been taken up and advanced by many workers in the field of soil science who have used it to replace older soil moisture constants as well as to aid in their interpretation. Chronologically, in 1920, Gardner (1) suggested that capillary potential gave a new interpretation to the soil moisture constants of Briggs and others. L. A. Richards (2) has given special consideration to the techniques of moisture measurement and to the expansion of thermodynamic principles to soil moisture energy.

Richards and Weaver (4), from their experimental results with pressure-membrane apparatus, using the free energy concept of soil moisture energy relationship, have found it convenient to divide the total forces involved in moisture retention by soil into two classifications: (1) those due to osmotic effects of dissolved materials in soil solution, and (2) all other forces. These authors point out that the osmotic effects may or may not be included in the so-called moisture potential. However, the moisture potential, when determined by suction plate, pressure plate, centrifuge, or tensiometer, is of practical use in evaluating the free energy of soil as depicted in the moisture sorption curves for most soils.

Moisture sorption curves essentially represent the soil moisture suction forces that must be overcome by plant roots if they are to extract water from soil at any moisture value. In these soils, the osmotic forces that arise from concentrations of dissolved materials in the soil solution at different moisture levels of the soil, or that are due to a concentration of these solutions about the root hairs as water is extracted from them by plant root uptake, have not been measured.

A short perusal of the petrographic studies by Stearns and McDonald, J. D. Dana, E. S. Dana, Whitman Cross, and H. S. Washington on Hawaiian lavas, will indicate that, from one lava flow to another, there is considerable diversity in the minerals and their chemical composition. Not only can this differentiation be noted in lava flows, but on the chain of islands from Kauai southeastward, there is a

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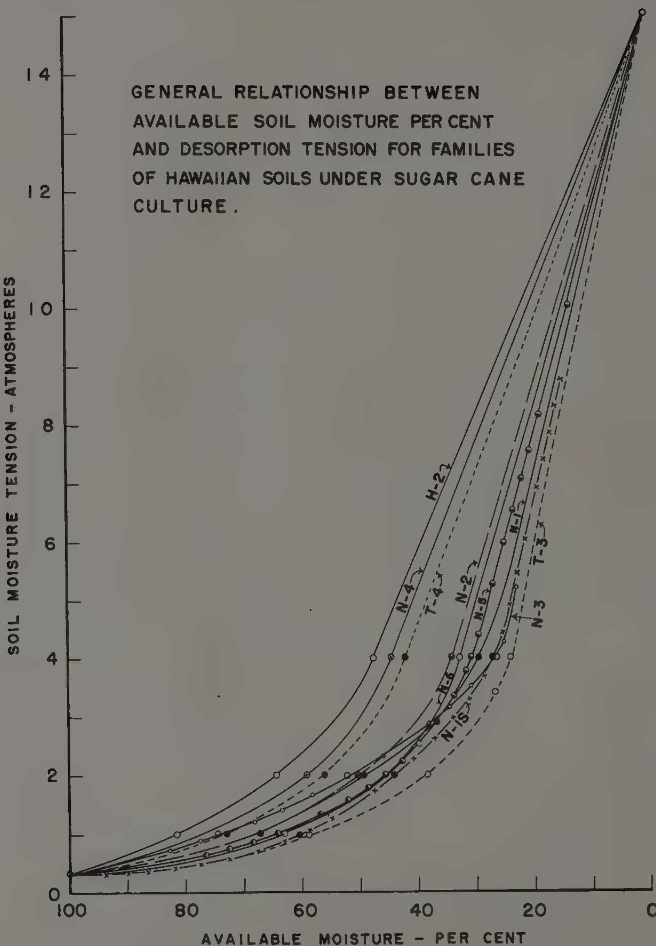
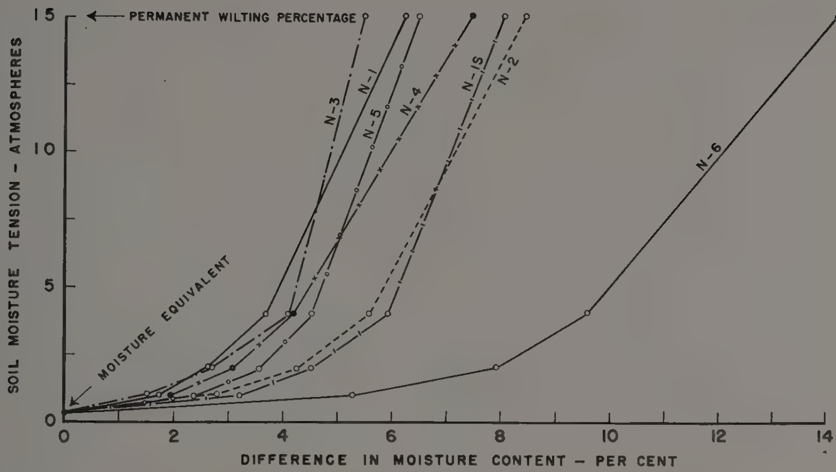
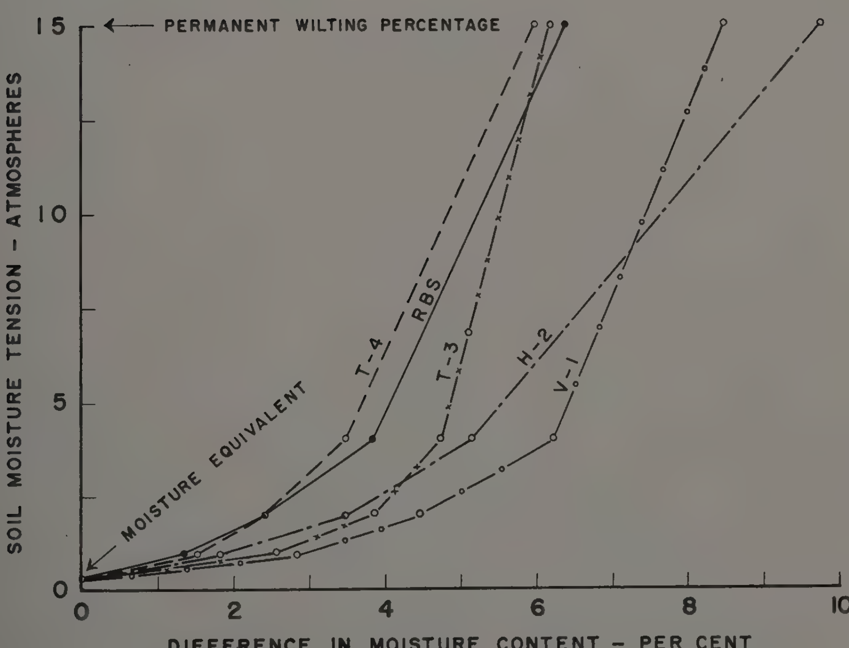


KEY TO SOIL SYMBOLS USED IN GRAPHS

GROUP	FAMILY	SYMBOL	NO. OF SAMPLES
Low Humic Latosol	Molokai	N–1	12
"	Molokai, stony phase	N–1S	3
"	Lahaina	N–2	8
"	Wahiawa	N–3	5
"	Kahana	N–4	7
"	Kohala	N–5	23
"	Waialua	N–6	2
Hydromorphic	Kalihi	H–2	12
Reddish Brown	—shallow	RBS	1
Humic Ferruginous Latosol	Haiku	T–3	5
"	Puhi	T–4	10
Alluvial	Kawaihapai	V–1	22


PERMANENT WILTING PERCENTAGE
MOISTURE EQUIVALENT
N-3
N-1
N-5
N-4
N-1S
N-2
N-6
SOIL MOISTURE TENSION - ATMOSPHERES
DIFFERENCE IN MOISTURE CONTENT - PER CENT


PERMANENT WILTING PERCENTAGE
MOISTURE EQUIVALENT
T-4
RBS
T-3
H-2
V-1
SOIL MOISTURE TENSION - ATMOSPHERES
DIFFERENCE IN MOISTURE CONTENT - PER CENT

pattern of chemical composition and mineral differentiation from one eruption center to the next.

Soils derived from the different lavas of these eruptive centers may therefore be expected to vary in their characteristics. In addition, the geological age and the advancement of weathering processes give rise to further differences in the secondary mineral make-up of soils.

It is little wonder that it has been difficult to classify and map the Hawaiian soils. The work of Sherman in attempting to fractionate and identify the clay minerals in the soils of Hawaii will be of great value in helping to establish order in tropical soil classification. When the determination of moisture sorption curves for different soil types was started, it was realized that the difficulties might be great. It was hoped that a basic curve for the moisture-holding characteristics of each soil type would be found. From the shape of many of the curves derived, the expected intergrading and mixing of different soil types have been found. At the same time, patterns of general behavior from many of the soil types and families have begun to emerge. These curves are not as accurate or as complete as would be desirable, but they represent the practically continuous processing of as many soils as could be characterized in two years of research. (Figures 1, 2 and 3)

Since the major acreage of cane under irrigation lies in the low humic latosols, these families were given priority. Humic ferruginous latosols, alluvials, and gray hydromorphics have followed in priority sequence, leaving the dark magnesium clays, humic latosols, regosols and some of the other types, still to be processed.

It will be noted that the curves presented herein do not go below one-third atm. tension or above 15 atm. tension. The former value checks very closely with the centrifuge-determined moisture equivalent value in the low humic latosol group. The curves were run on disturbed samples and the resulting changes in pore space would give fallacious values for tensions below one-third atm. Discrepancies in required tension values, found in irrigation experiments that attempt to define proper tensions for irrigation on the several islands, may hinge on the inaccuracy of the one-third atm. tension as a blanket value for the moisture equivalent in all island soil types. Within the last year, there have been hints of a similar situation in literature by workers in California and Utah. The re-evaluation will be time-consuming and laborious. It will, however, be worth while if it resolves some of the present uncertainties.

Since reproducible values for the one-third atm. tension were obtained and since they were found to agree closely with earlier moisture equivalent determinations by centrifuge for the low humic latosols, they are being used in the curves presented herein for the lowest tension values. The 15 atm. values approximate the permanent wilting percentage from pot studies. It is well understood that, in some cases, the soil moisture tension corresponding to the permanent wilting percentage may be as low as 12 and/or as high as 20 atm. Errors inherent in the technique of the determinations and the steep slopes of the tension curves tend to obscure accurate determination. It appears probable that physiological processes are adjustable over a sizeable tension range while, at the same time, moisture percentage range can be rather narrow.

In Figure 1, the moisture percentage between one-third atm. and 15 atm. has been taken as 100 per cent of the available moisture that can be stored in the

soil. Then the moisture values at the 1, 2, and 4 atm. tensions were taken and were expressed as the "per cent of available moisture" at the given tensions and were drawn in the appropriate freehand curves through the points so determined. Variations in total per cent moisture available in each family do not show in this type of presentation; so the spread of these values in the various families is shown in Figures 2 and 3.

It cannot be stressed too strongly that these are "mean" curves for the number of sample soils listed. Single determinations can and do vary considerably from the results presented herewith, but a trend is shown in each case which is considered real and valuable. Even at the present time, and as incomplete as the data are, any very wide variation from the curves shown should warrant a resurvey and possible correction in mapping classification for a field.

Too little is known about the physical and chemical composition of these soil families to discuss why any curve takes the slopes it does. The curves are, however, a valuable tool to the agriculturist in evaluating the extent of the moisture reserve he may call upon in a given soil family and, roughly, the dangerous depletion values of which he must beware. In lieu of a tension curve for his particular field or fields, or until a curve can be run for these fields, he will find these general trend curves of value if the general classification is known.

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WATER DISTRIBUTION STUDIES IN THE HAWAIIAN SUGAR INDUSTRY

ROGER P. HUMBERT[1]

The water requirements of the Hawaiian sugar industry are exceedingly, perhaps excessively, large. Annual rainfall in the Hawaiian Islands varies from a low of 10 inches in some leeward coastal areas to a high of over 400 inches on the windward sides of the larger volcanoes. As the moisture-laden trade winds rise over the slopes of the mountain ranges, they cool and drop their moisture on the watershed. A portion of the rainfall runs off and is impounded in reservoirs for irrigation purposes. A larger portion, however, seeps through the vegetation and percolates through the pervious volcanic soil and rock beneath to perched bodies or to lenses overlying the salty water. Water from these lenses is pumped to the surface for irrigation purposes.

On lands with less than 60 inches of annual rainfall, cane requires supplemental water. About 400 billion gallons of water (2) are used annually for sugar cane irrigation, approximately half of which is pumped water. Since it is extremely costly to maintain the ditch systems in surface water development and to pump water from the greater depths, it was felt that a critical analysis of the efficiency of water should be made.

METHODS OF APPLYING IRRIGATION WATER

All irrigation water is carried to furrows by means of flumes, pipes and open ditches. High labor costs have forced a change from earlier short line systems of irrigation (1) to present long line methods of distribution. Since the introduction of the Waialua concrete flume (2), the herringbone system of irrigation has been widely used. It is used on slopes ranging up to 45 per cent. The grade of furrow varies from approximately two per cent adjacent to the flume to zero where the two lines converge.

Continuous long line irrigation is practiced on the more impermeable soils. These soils require a slow and prolonged application of water to ensure satisfactory penetration. The introduction of aluminum flumes has resulted in an increased usage of the continuous long line system of irrigation.

The level ditch system of irrigation is used on flatter terrain. The principal disadvantage of this system on steeper slopes is that the ditches occupy considerable areas.

The rate of water application varies with the season of the year, the age of

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the crop, the type of soil and the amount of water available. The average number of irrigations used in growing a 22- to 24-month crop of cane varies between 20 and 50. Plantations that have limited water for irrigation and soils with high water-holding capacities, apply less water with the smaller number of irrigations. Plantations with soils that are highly pervious and of low water-holding capacity or that are impermeable and thus limit water penetration, require the larger number of rounds of irrigation.

The amount of water applied per round varies from one to eight acre inches. Uneven distribution of water is the principal reason for the higher rates of application.

PROCEDURE FOR STUDYING WATER DISTRIBUTION

The amount of information that could be obtained by digging pits and studying wetting patterns following irrigations is limited by the high manpower requirements and high cost of labor. Intensive studies of water distribution, using radioactive materials and tracer techniques, were initiated in 1951. Hawaiian soils have the capacity to effectively fix phosphorus. Initial trials with water containing P 32 gave a reading at the soil surface of X counts per minute when one acre inch of water was applied, 2X counts per minute when two acre inches of water were applied, 3X for three acre inches, etc. Field studies using radiocative phosphorus and radioactive rubidium, started at Waialua Agricultural Company, spread rapidly to the other irrigated plantations. Tests, completed in 1951 and 1952, included soil profile studies of wetting patterns to correlate soil activity readings with water penetration at five different stations along the irrigated line. The activity readings were found to be sufficiently reliable so that the costly digging could be eliminated in the tests conducted in 1953.

The information obtained for each test is as follows:

1. Slope of each 10-foot section along the furrow.
2. Irrigation system.
3. Soil type.
4. Age of crop.
5. Irrigation interval: normal, and that preceding test.
6. Water flow in minutes at each 10-foot marker.
7. Rate of flow of water from the flume.
8. Amount of water infiltrated at five selected stations along the cane line.

Pre-Irrigation Preparation

1. Place a series of sheet metal baffles at the head of the line to mix the rubidium stock solution with the irrigation water.

2. Select five stations along the line, the first being 20 feet from the head and the last a minimum of 10 feet from the end of the line.

3. Place four water-sampling bottles, two nails and a ladle at each station.

4. Dilute a solution containing approximately 1.5 millicuries of radioactive rubidium to six liters with clear water.

5. Select the orifice for the metering device to be used for the irrigation according to the estimated time of irrigation. The orifice selected should deliver about six liters of the rubidium solution in that period.

6. Set up the rubidium delivery station above the mixing baffles.

Irrigation of the Line

1. Open the irrigation water inlet and the valve of the rubidium solution delivery tube just as the water reaches it.
2. Record the accumulated time required for the water front to reach each of the 10-foot marks along the cane line.
3. Take four water samples at the outlet of the baffles and at each of the five sampling stations. The time intervals between samples 1 and 2 and samples 2 and 3 vary with the estimated time of irrigation as follows:

For irrigation 30 mins. or less	3 mins.
" " 1 hr. " "	5 "
" " 2 "	10 "
" " 3 "	15 "

The first sample is taken when the water reaches each station and the last sample when the water is shut off.

4. Determine the width of line irrigated by measuring the distance across the cane line from water line to water line at each sampling station. This is done after taking the third water sample. Peg two nails at the water lines for subsequent soil sampling.
5. Follow the usual plantation practice in shutting off the water, with a notation on data sheet as to the practice employed.
6. At the signal to end the irrigation, close the water inlet and the valve of the rubidium solution delivery tube and take the water samples at all the stations.
7. Take notes as to length of time the water "stands" in any sections of the line after irrigation.

After-Irrigation

1. Make field activity readings with a Berkeley portable scaler, No. 2080, at all the 10-foot marks, including the sampling stations.
2. Take soil samples at each sampling station. The sample at a particular station consists of six plugs of soil one inch in depth taken from water line to water line. A composite 50-gram sample from each station is used for laboratory counting.
3. Make an integrated sample from the water samples collected at each station. The volumes of each sample taken for the integrated sample correspond to the time intervals between samples. A 50 m1 sample is used for counting.
4. Determine with a Tracer Lab 64 scaler the radioactivity counts on the six water and five soil samples involved in each irrigation test.

RESULTS OF RADIO RUBIDIUM TESTS

Ninety-four tests covering the principal types of soil and irrigation systems on irrigated plantations were completed in 1953. The data were used to characterize the efficiency of water distribution under a given set of conditions with regard to (1) soil type, (2) length and slope of line, (3) volume of water discharge, and (4) time of irrigation.

Since the irrigations represented the normal for these conditions, they were analyzed to improve water distribution with the present field layout. Suggestions were also made for improvements in future field designs.

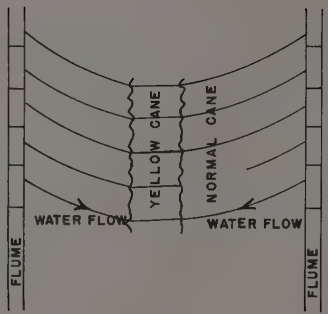


Figure 1. Herringbone system of irrigation.

HERRINGBONE SYSTEM: The herringbone system was found to have several outstanding weaknesses in water distribution. (Figure 1) Studies during periods of drought and during periods of excessive rainfall point up these weaknesses. With heavy rainfall, the water accumulates in the bellies of the herringbone and eventually breaks through. (Figure 2) Reshaping these lines is a costly procedure, and the re-formed banks often wash out again during long periods of wet weather.

When water stands in the bellies of the lines and keeps the soils saturated or nearly saturated, the cane often suffers from a lack of oxygen. Bands of yellow cane occasionally occur in the bellies of the herringbone. Figure 3 shows typical root systems of year-old cane taken in Field 77 at Hawaiian Commercial and Sugar Company in February 1951. The cane on the left has enjoyed normal growth as may be seen from the size of the stalk and the length of the internode. In the period of saturation that preceded the excavation, the root hairs died, secondary rootlets failed to develop and the primary roots began to break down. This condition resulted in an oxygen deficit and yellowing of the plant. Nearer the flume and outside of the yellow band of cane, the cane was growing satisfactorily. Here a detailed examination of the roots showed that oxygen was being obtained from the bank of soil in the interline. The roots were climbing the banks in an attempt to get oxygen. These roots had normal fibrous secondary roots and appeared to be in a healthy condition.

An examination of the water distribution data in Table 1 shows weaknesses at stations C and D. These stations represent the section from half to three-fourths of the distance down the line. In the herringbone system, this section of the line normally receives considerably less water than other sections. Figure 4 shows the effect of poor water distribution following an extended drought. The cane in the foreground, near the flume, is growing normally while that in the center is suffering from a lack of water. The cane in the background, in the belly of the herringbone where the water accumulates, is growing satisfactorily.

A typical example of an irrigation in which inadequate amounts of water were applied in the middle portion of the line is shown in Figure 5. A slightly lower grade in this section would have given a better distribution of water. With the present layout, the volume of water discharge and the length of time that water was allowed to flow into the line were satisfactory.

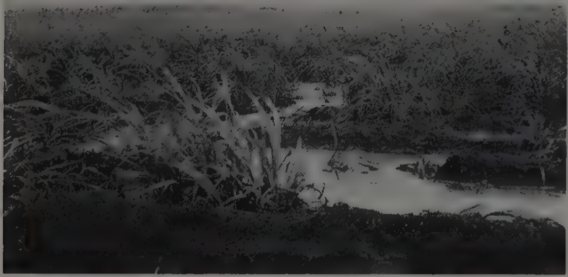


Figure 2. Erosion in field of young cane. Oahu Sugar Company, March 1951.

Figure 3. Root systems of year-old cane: left, cane pulled from the water-saturated soils of the belly of the herringbone; right, normal cane with a part of its root system growing up the bank of soil to obtain air. H C & S Co. February 1951.

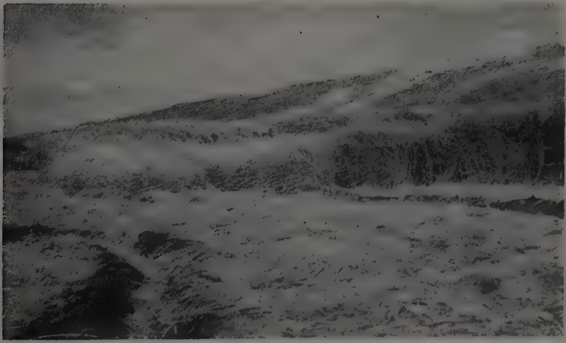
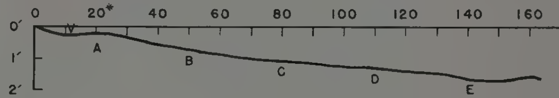


Figure 4. The effect of a poor water distribution in a herringbone system of irrigation.

IRRIGATION TEST M-23 7/20/53 H.C.& S. Co. FIELD: 401 MAUKA

PLANT AGE 3 MOS. NORMAL IRRIGATION INTERVAL: 12 DAYS HERRINGBONE SYSTEM SOIL TYPE: LOW HUMIC LATOSOL, LAHAINA FAMILY
IRRIGATION INTERVAL OF TEST: 13 DAYS

DISTANCE FROM FLUME IN FEET



RATE OF WATER FLOW AT FLUME: 14.3 GAL./MIN.

PER CENT SLOPE		-2.5	+1.0	-2.0	-2.0	-1.5	-1.5	-1.0	-1.0	-1.0	-0.5	-1.0	-0.5	-1.0	-2.0	0	+1.0	-0.5
WATER FLOW IN MINUTES	72	71	69	65	63	61	58	54	52	50	47	44	40	37	35	28	18	17
FIELD SOIL READINGS IN COUNTS/MINUTE AT 9"																		
OVEN DRY SOIL READINGS COUNTS/MINUTE			10556			13085			3765			4899			5080			
CALCULATED INCH IRRIGATION			6.95			10.04			3.37			5.14			6.43			
WIDTH OF WATER LINE IN INCHES			14			14			15			16			26			
CALCULATED ACRE INCH IRRIGATION			1.60			2.31			0.84			1.39			2.76			

LEGEND: * = CHANNELING; V = PONDING

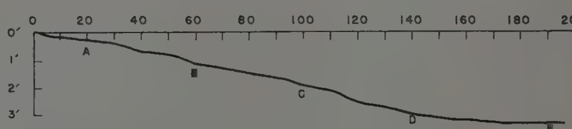
Figure 5. Water distribution of a typical cane line in the herringbone system, showing a weakness of under-irrigation in the middle portion of the line.

The herringbone system of irrigation gives a reasonably good distribution of water where proper grades of line and rate and time of water flow are suited to the soil type. Figure 6 shows an example of an excellent irrigation.

IRRIGATION TEST H-10 9/17/53 KOHALA SUGAR Co. FIELD UNION 4

2nd RATOON AGE 1.0 MO. NORMAL IRRIGATION INTERVAL: 15 DAYS HERRINGBONE SYSTEM SOIL TYPE: LOW HUMIC LATOSOL, KOHALA FAMILY
IRRIGATION INTERVAL OF TEST: 20 DAYS

DISTANCE FROM FLUME IN FEET



RATE OF WATER FLOW AT FLUME: 77.3 GAL./MIN

PER CENT SLOPE		-1.7	-0.9	-1.6	-2.7	-0.8	-3.8	-1.1	-2.1	-1.8	-2.7	-1.8	-4.4	-1.6	-2.4	-1.3	-0.7	-0.8	-0.3	0
WATER FLOW IN MINUTES	32	31	31	31	30	30	29	29	28	28	27	26	25	24	23	23	21	19	15	9
FIELD SOIL READINGS IN COUNTS/MINUTE AT 9"		2015	2437	1644	1548	1246	1665	1704	1828	1853	2066	1622	1689	1550	1019	1180	1214	1051	797	739
OVEN DRY SOIL READINGS COUNTS/MINUTE			6101				4050				6409				3177					4019
CALCULATED INCH IRRIGATION			6.45				4.76				8.52				5.04					8.39
WIDTH OF WATER LINE IN INCHES			24				20				18				19					16
CALCULATED ACRE INCH IRRIGATION			2.58				1.57				2.56				1.56					2.18

Figure 6. An excellent distribution of water with the herringbone system of irrigation.

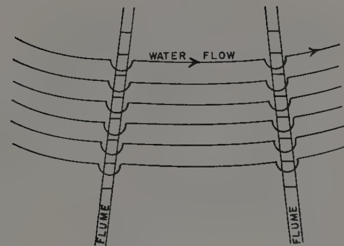


Figure 7. Continuous long line system of irrigation.

CONTINUOUS LONG LINE SYSTEM: The continuous long line system of irrigation gives a reasonably good distribution of water. (Figure 7) The data in Table 2 show fluctuation among the five stations to be a little smaller than with the herringbone system. The larger mean acre-inch application for Station E is due to those tests where the lines were closed off, and water accumulated. This was not observed in the majority of the tests where the water flow was continuous beneath the next flume. The mean length of line was longer, the mean flume discharge was smaller and the mean time of water flow was shorter than were corresponding values for the herringbone system of irrigation. It is of interest to note the higher average slope of line under the continuous long line system of irrigation. The resultant lower acre-inch applications are satisfactory where this system of irrigation has been used on the more impervious soils with higher water-holding capacity.

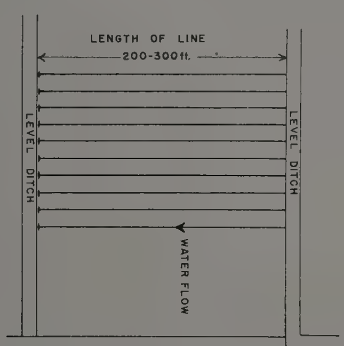


Figure 8. Level ditch system of irrigation.

LEVEL DITCH SYSTEM: The data in Table 3 show that the level ditch system of irrigation results in the best distribution of water. (Figure 8) With one exception, test K-15, the application of water was reasonably satisfactory. Under this system of irrigation, the lines are a little shorter, on the average, the volume of flume discharge is lower and the time of water flow is briefer than with either the herringbone or continuous long line systems. The average per cent slope of the lines is the same as for the herringbone and less than for the continuous longline system.

Even though the distribution of water under the level ditch system is good, it is not an economical system to use on steep land. The cane area lost to level ditches rises rapidly as the slope of the field increases.

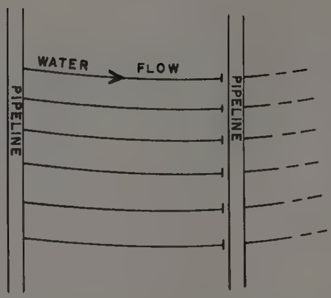


Figure 9. Pipeline system of irrigation.

PIPELINE SYSTEM: The data in Table 4 show a fairly satisfactory mean distribution of water. (Figure 9) An examination of the individual tests, however, shows the presence of weak sections, particularly near the ends of the lines.

The comparatively high rate of flume discharge and the steep average slope emphasize the importance of the time of water shutoff. The mean time of water flow of 39 minutes accounts for the comparatively low acre-inch applications.

VOLUME OF WATER DISCHARGE

Since the present field layouts will be used for periods of from two to eight years, depending upon the time before the next plowing and planting, it was felt necessary to study the effects of volume of water discharge on velocity of flow and distribution of water in these layouts. Figure 10 shows the relation of velocity flow to flume discharge rate. For every increase of one gallon per minute in flume discharge, the velocity of the water front increases .102 feet per minute. Estimates

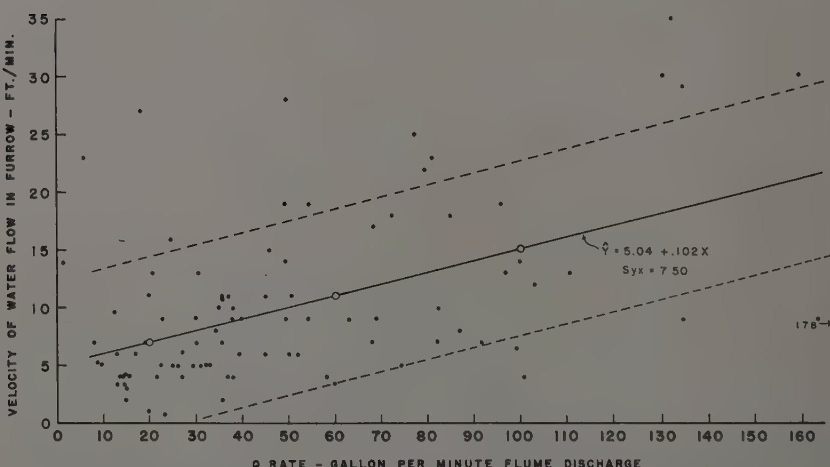
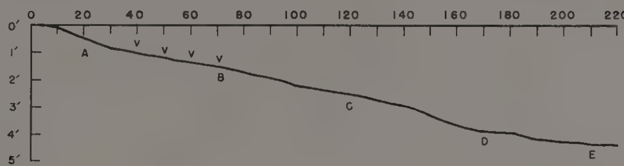


Figure 10. Relation of velocity of water flow in the furrow to Q rate (gallons/min. flume discharge); estimated values from linear regression and zone of probable values indicated by the standard error of estimate.

IRRIGATION TEST H-2 8/21/53 KOHALA SUGAR Co. FIELD UPOLU 12

PLANT AGE 2 MOS. NORMAL IRRIGATION INTERVAL: 13 DAYS HERRINGBONE SYSTEM SOIL TYPE: LOW HUMIC LATOSOL, KOHALA FAMILY
IRRIGATION INTERVAL OF TEST: 13 DAYS

DISTANCE FROM FLUME IN FEET



ER CENT SLOPE		-0.8	-4.2	-3.5	-1.8	-1.8	-1.8	-1.5	-2.0	-2.5	-2.5	-1.8	-1.8	-1.8	-2.5	-3.0	-4.2	-2.3	-0.5	-1.8	-1.3	-1.5	0
ATE OF WATER FLOW AT FLUME: 60.3 GAL./MIN.																							
ATER FLOW IN MINUTES	70	69	69	68	67	66	65	64	62	61	59	57	55	53	50	47	44	40	33	28	19	10	0
IELD SOIL READINGS IN COUNTS/MINUTE AT 9″		789	665	1183	1265	1323	854	682	386	591	337	263	312	304	222	131	378	189	82	131	123	90	-

	A	B	C	D	E
VEN DRY SOIL READINGS COUNTS/MINUTE	9272	5192	3183	996	121
ALCULATED INCH IRRIGATION	18.19	11.77	8.10	2.86	0.43
IDTH OF WATER LINE IN INCHES	14	13	14	19	10
ALCULATED ACRE INCH IRRIGATION	4.18	2.59	1.94	0.92	0.02

EGEND: V = PONDING

Figure 11. An example of a very poor distribution of water.

of velocity for a given flume discharge rate would be expected to fall within the range of the zones marked off on either side of the regression line, except once in three times.

In many of the tests listed in Tables 1–4 inclusive, an improved distribution of water is possible by varying the rate of flume discharge. Figure 11 represents an example of very poor water distribution. Increasing the flume discharge rate could improve irrigation in this line with the present layout.

Other instances were observed where excessive amounts of water piled up at the ends of the lines. This condition normally occurs on impervious soils graded to fairly steep slopes and irrigated with a larger volume of water than is desirable.

LINE SLOPE

With fields that are scheduled to be plowed and planted following the harvest of this present crop, particular emphasis is placed on line-slope limitations. Hawaiian soils vary from highly impermeable to very pervious soils. Marked differences in infiltration rates make it necessary to vary the length of line, the grade of line, and the volume of water flow in order to obtain a satisfactory distribution of water.

Figure 12 shows the relation between velocity of water flow in the furrow and the slope of line. For each increase of one per cent in slope, the velocity of flow increases 1.89 feet per minute. Estimates of velocity from slope should fall within the range marked off on either side of the regression line, except once in three times.

The influence of slope on distribution of water can be seen in Figures 13, 14 and 15. In Figure 13, the relatively high rate of flow from the flume, coupled with the low, one per cent, slope of line, has given a uniform distribution of water. In Figure 14, an uneven distribution of water is indicated by the higher acre-inch value at station E. Lower acre-inch values occur at all stations on the steeper

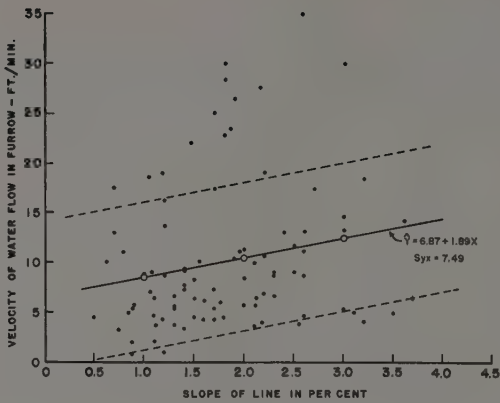


Figure 12. Relation of velocity of water flow in the furrow to slope of line; estimated values from linear regression and zone of probable values indicated by the standard error of estimate.

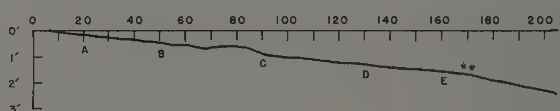
slopes nearer the flume. The high rate of water flow from the flume, coupled with the relatively high, two per cent, slope, resulted in only limited penetration of water along the line and an accumulation of water in the belly of the herringbone. A reduced head of water and a longer period of irrigation would have resulted in a better distribution of water for this layout on this soil. Figure 15 shows the distribution of water under the same conditions as in Figures 13 and 14, except that the line had a three per cent grade. A very uneven distribution of water is indicated by the markedly higher acre-inch value at Station E.

This series of three tests in the same field with the same soil type, under the same system of irrigation, shows the importance of having proper slopes for a given soil and length of line.

IRRIGATION TEST M-17 7/15/53 WAILUKU SUGAR Co. FIELD 36 (1% GRADE)

PLANT AGE 5 MOS. NORMAL IRRIGATION INTERVAL: 15 DAYS HERRINGBONE SYSTEM SOIL TYPE: LOW HUMIC LATOSOL, LAHAINA FAMILY
IRRIGATION INTERVAL OF TEST: 15 DAYS

DISTANCE FROM FLUME IN FEET



PER CENT SLOPE		-0.6	-1.0	-0.8	-1.2	-1.2	-1.0	-1.2	+0.5	-2.6	-1.2	-1.1	-1.1	-1.1	-0.9	-1.1	-1.1	-1.1	-2.0	-1.8	-1.5	-1.3
RATE OF WATER FLOW AT FLUME: 100.7 GAL./MIN.																						
WATER FLOW IN MINUTES	15	15	14	14	14	13	13	12	12	11	11	10	9	9	8	7	6	5	4	4	1	1
FIELD SOIL READINGS IN COUNTS/MINUTE AT 9″		305	600	468	663	734	477	409	316	349	303	268	321	209	224	160	163	127	169	119	48	
OVEN DRY SOIL READINGS COUNTS/MINUTE			2886			3080				1806				2097			801					
CALCULATED INCH IRRIGATION			4.22			4.73				3.41				6.35			2.78					
WIDTH OF WATER LINE IN INCHES			26			24				24				23			20					
CALCULATED ACRE INCH IRRIGATION			1.81			1.89				1.37				2.03			0.92					

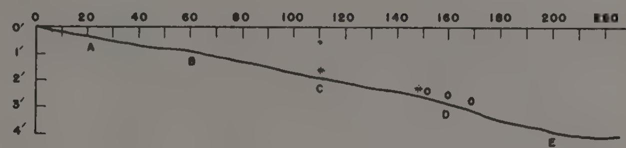
LEGEND: ** = LINE WAS WET FROM 170 FEET TO END OF LINE BEFORE RUBIDIUM IRRIGATION WAS APPLIED. THEREFORE, STATION E WAS LOCATED AT 160 FEET.

Figure 13. Water distribution in a low humic latosol in a herringbone system at a 1 per cent grade of line.

IRRIGATION TEST M-15 7/15/53 WAILUKU SUGAR Co. FIELD 36 (2 % GRADE)

PLANT AGE 5 MOS. NORMAL IRRIGATION INTERVAL: 15 DAYS HERRINGBONE SYSTEM SOIL TYPE: HUMIC LATOSOL, LAHAINA FAMILY
IRRIGATION INTERVAL OF TEST: 15 DAYS

DISTANCE FROM FLUME IN FEET



PER CENT SLOPE -2.3 -1.4 -1.9 -1.8 -2.3 -1.3 -1.6 -2.3 -1.5 -2.0 -1.8 -1.8 -2.2 -1.7 -2.2 -1.7 -3.4 -2.6 -2.4 -1.7 -1.8 -0.6 +0.2
RATE OF WATER FLOW AT FLUME: 31.6 GAL./MIN.

WATER FLOW IN MINUTES 13 13 12 12 12 11 11 11 10 10 10 9 9 8 8 7 6 6 6 5 4 3 2 1
FIELD SOIL READINGS IN COUNTS/MINUTE AT 9″ 424 349 321 393 294 361 294 299 281 246 143 180 213 119 94 88 66 103 72 108 119 66

OVEN DRY SOIL READINGS COUNTS/MINUTE 1288 699 1028 755 562

CALCULATED INCH IRRIGATION 1.82 1.21 2.46 3.71 18.15
WIDTH OF WATER LINE IN INCHES 25 23 18 19 28
CALCULATED ACRE INCH IRRIGATION 0.76 0.46 0.78 1.19 7.62

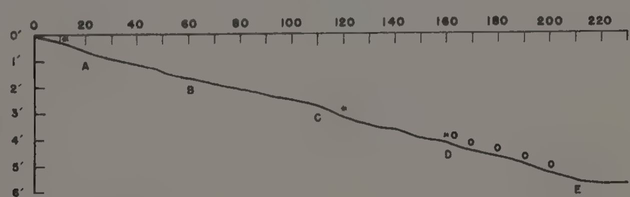
LEGEND: # = CHANNELING; O = POOR GROWTH

Figure 14. Water distribution in a low humic latosol in a herringbone system at a 2 per cent grade of line.

IRRIGATION TEST M-16 7/15/53 WAILUKU SUGAR Co. FIELD 36 (3% GRADE)

PLANT AGE 5 MOS. NORMAL IRRIGATION INTERVAL: 15 DAYS HERRINGBONE SYSTEM SOIL TYPE: LOW HUMIC LATOSOL, LAHAINA FAMILY
IRRIGATION INTERVAL OF TEST: 11 DAYS

DISTANCE FROM FLUME IN FEET



PER CENT SLOPE -3.3 -3.3 -2.9 -2.4 -2.8 -1.8 -1.9 -2.1 -3.4 -0.8 -2.7 -4.2 -3.0 -2.3 -3.2 -2.4 -3.2 -2.1 -2.6 -2.8 -3.5 -1.1 +0.2
RATE OF WATER FLOW AT FLUME: 67.5 GAL./MIN.

WATER FLOW IN MINUTES 17 17 16 16 16 16 15 15 14 14 13 13 12 12 11 11 10 9 8 7 6 5 4 1
FIELD SOIL READINGS COUNTS/MINUTE AT 9″ 231 867 960 580 569 496 516 873 830 334 442 248 257 369 306 222 332 338 222 145 242 171 108

OVEN DRY SOIL READINGS COUNTS/MINUTE 604 2205 1095 419 1107

CALCULATED INCH IRRIGATION 0.42 1.91 1.39 1.01 50.23
WIDTH OF WATER LINE IN INCHES 24 15 20 14 26
CALCULATED ACRE INCH IRRIGATION 0.17 0.57 0.46 0.23 23.75

LEGEND: # = CHANNELING; O = POOR GROWTH.

Figure 15. Water distribution in a low humic latosol in a herringbone system at a 3 per cent grade of line.

SUMMARY

1. The results of three years of research on the distribution of water in furrow irrigation are presented.

2. A detailed procedure for the use of radioactive materials and tracer techniques is presented. The procedure is being further tested with known volumes of water in order to check the accuracy of the calculated acre-inch irrigations. It is being used at present for detecting gross weaknesses in water distribution patterns in the presently used systems of irrigation and to interpret the results in terms of lengths and grades of lines and volumes of water used.

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Table I. Water Distribution Data from the Herringbone System of Irrigation

Test No.	Irrigation System	Soil Type	Age of Cane Months	Length of Line Feet	Av. Slope Per cent	Flume Dischg. Gal./min.	Time of Water Flow Minutes	Calculated Acre Inch Irrigation Stations				
								A	B	C	D	E
O– 2	Herringbone	N2	12.3	180	0.8	9	180	2.34	2.48	1.06	0.95	0.34
O– 9	"	N3	13.9	230	1.2	20	291	2.15	6.19	3.64	4.63	4.94
O–10	"	N3	13.9	230	1.1	31	120	3.70	4.87	1.58	1.79	3.10
O–11	"	N3	13.9	230	1.1	91	50	3.90	3.50	2.77	3.11	5.46
O–12	"	N2	2.7	290	1.5	52	237	13.98	6.17	2.42	4.57	1.77
O–13	"	N2	2.7	290	1.7	35	151	1.55	2.71	1.24	3.12	0.95
O–14	"	N2	2.7	290	1.8	79	34	..	2.72	1.02	1.25	1.50
O–15	"	N2	2.3	300	0.8	24	209	4.22	4.98	4.28	1.22	1.15
M– 3	"	V1	3.0	240	1.3	88	45	1.82	2.58	1.49	2.38	1.33
M– 5	"	V1	9.0	190	1.4	14	71	1.10	1.36	2.71	0.92	1.82
M– 6	"	V1	4.0	190	1.4	45	51	1.00	3.37	2.51	1.58	6.60
M–15	"	N2	5.0	224	1.9	82	13	0.76	0.46	0.78	1.19	7.62
M–16	"	N2	5.0	230	2.5	68	17	0.17	0.57	0.46	0.23	23.75
M–17	"	N2	5.0	205	1.2	101	15	1.81	1.89	1.37	2.03	0.92
M–27	"	V1	2.0	210	1.6	72	27	2.98	4.72	2.01	0.91	0.82
M–23	"	N2	3.0	165	1.1	14	72	1.60	2.31	0.84	1.39	2.76
M–24	"	N2	3.0	115	1.4	8	48	0.35	1.05	0.86	0.54	1.44
H– 1	"	N2	2.0	220	1.8	13	40	0.88	1.80	0.72	0.30	0.38
H– 2	"	N5	2.0	220	2.0	60	70	4.18	2.59	1.94	0.92	0.02
H– 3	"	N5	1.0	160	1.9	21	165	3.29	6.48	1.70	0.65	..
H– 7	"	N5	3.9	140	2.1	40	36	1.64	2.00	5.21	2.46	1.52
H– 8	"	N2	0.8	290	1.6	135	8	1.19	0.71	1.02	2.12	1.80
H– 9	"	N5	1.7	290	1.4	159	22	4.52	1.07	6.09	4.30	4.45
H–10	"	N5	1.0	195	1.7	77	32	2.58	1.57	2.56	1.56	2.18
	Mean ± Sta	ndard Error	4.8	222 ± 10	1.5 ± .1	56 ± 8	84 ± 16	2.68	2.84	2.10	1.84	3.33

At P.05: LSD = 1.17 with M–16(E) omitted

Table II. Water Distribution Data from the Continuous Long Line System of Irrigation

Test No.	Irrigation System	Soil Type	Age of Cane Months	Length of Line Feet	Av. Slope Per cent	Flume Dischg. Gal./min.	Time of Water Flow Minutes	Calculated Acre Inch Irrigation Stations A	B	C	D	E
O–16	Continuous Long Line	N1	1.2	220	1.1	15	291	2.46	2.50	0.70	0.85	0.47
O–17	"	N1C	4.7	180	0.8	37	60	1.57	2.22	3.34	3.73	3.98
O–18	"	N2	3.3	300	0.0	16	107	1.67	1.00	1.14	1.42	..
O–19	"	N2	3.5	270	2.6	31	26	0.34	0.38	0.98	0.42	0.58
O–20	"	H2	2.0	250	2.0	17	60	0.64	0.39	1.71	0.07	1.02
K– 1	"	N1	5.2	240	1.9	15	88	3.25	2.05	1.66	0.25	1.66
K– 2	"	N1	4.2	305	2.1	27	93	0.22	2.71	2.14	0.93	2.94
K– 3	"	N1	13.2	295	2.9	32	82	2.17	2.53	0.96	0.80	0.79
K– 4	"	N1	9.3	225	1.0	9	173	1.63	0.97	1.10	0.74	0.35
K– 5	"	N1	12.3	210	1.5	33	110	0.69	1.54	2.07	1.67	14.44
K– 6	"	N1	12.7	220	1.7	54	68	2.05	2.10	1.72	1.24	1.15
K– 7	"	N1	12.7	260	2.1	58	103	3.86	5.24	2.72	4.41	2.65
K– 8	Long Line	N1	10.0	350	2.4	46	38	0.66	1.92	1.31	1.39	4.47
K– 9	"	N4	8.0	190	3.1	25	47	1.86	0.75	0.41	1.23	2.06
K–10	"	N4	10.0	350	2.4	112	35	2.42	2.34	3.39	3.88	2.56
K–11	"	N4	6.0	155	4.9	38	52	3.52	2.72	1.85	0.81	0.60
K–12	Continuous Long Line	N4	4.4	375	0.9	134	93	13.22	5.45	4.26	3.03	..
K–13	"	N4	4.4	290	1.4	23	36	1.10	1.12	0.92	1.19	1.69
K–14	"	N4	5.0	340	1.7	24	95	2.56	2.45	1.52	3.09	1.38
K–17	"	N1	3.8	320	1.9	52	37	1.60	2.37	1.39	1.00	3.69
K–18	Long Line	N1 & H3	4.0	240	0.5	85	38	1.56	1.97	1.93	0.88	1.05
K–19	Continuous Long Line	N1	4.3	170	1.8	30	32	1.58	1.74	1.73	1.27	..
K–20	"	N4S	3.5	130	3.8	49	21	0.83	2.38	2.08	2.22	2.44
K–22	Long Line	N4S	3.5	230	1.8	74	64	8.33	5.22	2.50	1.41	1.37
M– 4	Continuous Long Line	N2	10.0	240	1.5	101	62	1.80	2.54	4.14	2.84	2.37
M–18	"	V1	3.3	195	2.1	49	8	0.30	0.36	0.55	3.87	0.57
M–19	"	V1	3.3	208	2.9	130	9	1.04	1.33	0.98	0.58	5.65
M–20	"	V1	3.3	190	1.1	96	13	1.24	0.86	1.82	1.45	1.29
M–32	Continuous Long Line	V1	2.0	217	1.9	36	28	1.10	1.25	2.83	1.95	0.39
M–33	"	V1	2.0	203	1.5	37	42	1.43	1.07	0.74	0.98	..
H–16	"	A5	12.0	200	2.1	38	43	3.17	1.42	2.16	1.02	2.30
	Mean ± Standard Error		6.0	244 ± 11	1.9 ± .2	49 ± 6	66 ± 10	2.25	2.03	1.83	1.63	2.37

At P.05: LSD = .95

Test No.	Irrigation System	Soil Type	Age of Cane Months	Length of Line Feet	Av. Slope Per cent	Flume Dischg. Gal./min.	Time of Water Flow Minutes	Calculated Acre Inch Irrigation Stations				
								A	B	C	D	E
O– 7	Level Ditch	N1	2.0	300	1.9	6	16	0.17	0.23	0.05	0.10	0.50
O– 8	"	N1	2.0	570	1.9	19	72	0.55	0.11	0.16	0.10	0.08
K–15	"	H3	3.1	235	0.4	38	46	3.05	2.61	1.36	4.13	24.12
K–21	"	T4	1.3	140	1.8	132	12	2.39	1.34	0.64	1.03	1.54
K–23	"	T4	2.1	150	1.5	32	20	0.87	0.97	0.97	0.77	0.56
K–24	"	T4	6.2	180	2.0	49	41	3.28	2.87	3.06	2.95	5.11
M– 7	"	V1	1.5	180	0.9	36	95	5.52	2.39	1.54	1.45	..
M– 8	"	V1	1.2	254	0.9	39	120	4.02	5.01	3.12	..	..
M–11	"	V1	2.0	163	1.2	15	52	1.33	1.35	1.19	1.87	1.39
M–12	"	V1	2.0	139	1.3	13	45	1.37	5.23	0.87	1.07	1.04
M–13	"	N1	3.0	130	1.2	21	90	6.92	3.84	4.31	1.44	1.97
M–14	"	N1	3.0	135	0.8	26	50	2.43	2.42	2.03	0.99	0.89
M–28	"	N2	4.0	105	1.1	15	75	1.29	2.47	1.32	1.35	2.00
M–29	"	N2	4.0	167	1.3	63	42	8.41	2.11	3.67	1.87	..
M–34	"	R1	1.5	120	0.8	21	51	4.18	1.86	3.16	5.36	10.21
M–35	"	R1	1.5	200	2.1	82	63	3.14	2.04	1.67	11.70	3.83
H– 4	"	A5	1.0	320	3.3	94	40	1.65	3.22	10.40	1.46	2.90
H– 5	"	A4	6.0	210	2.8	104	40	4.41	7.92	2.21	1.29	1.08
	Mean ± Standard Error		2.6	205±26	1.5±.2	45±8	54±7	3.05	2.70	2.32	2.29	3.81

At P.05: LSD = 2.21

Table IV. Water Distribution Data from the Pipeline System of Irrigation

Test No.	Irrigation System	Soil Type	Age of Cane Months	Length of Line Feet	Av. Slope Per cent	Flume Dischg. Gal./min.	Time of Water Flow Minutes	Calculated Acre Inch Irrigation Stations				
								A	B	C	D	E
M– 1	Pipe Line	N1S	10.5	140	1.8	27	43	0.62	1.48	1.80	0.83	0.35
M– 2	"	N2	11.0	130	2.5	29	25	1.07	1.37	0.92	1.13	0.35
M– 9	"	N1S	14.0	160	1.3	179	20	1.76	1.45	1.90	1.07	0.66
M–10	"	N4D	4.0	340	1.5	68	49	1.55	3.82	1.66	2.43	..
M–21	"	N1S	12.0	340	3.1	37	81	1.06	1.07	1.31	1.13	0.95
M–22	"	N2	2.0	210	1.9	46	33	1.07	1.35	1.85	3.25	3.51
M–25	"	N1S	6.0	200	1.9	19	57	2.23	1.50	1.60	1.66	1.05
M–26	"	N4D	4.0	170	2.1	69	24	1.18	1.67	1.95	1.48	2.21
M–30	"	N1S	12.0	210	1.6	83	28	1.12	0.44	0.92	0.89	3.74
M–31	"	N1S	7.0	150	1.3	22	48	0.67	1.41	0.72	2.42	2.00
M–36	"	V1S	11.0	180	1.6	99	28	1.73	1.51	0.08	1.37	0.44
M–37	"	N1S	10.0	270	1.6	50	46	2.50	1.07	1.01	0.95	0.57
M–38	"	N2	12.0	320	2.6	37	30	0.74	0.82	0.39	0.91	5.28
M–39	"	N4D	4.0	280	3.0	49	18	0.78	0.81	1.77	1.38	0.20
M–41	"	N2	4.0	320	2.2	30	52	1.38	1.82	2.26	1.25	1.25
	Mean ± Standard Error		8.2	228±19	2.0±.2	56±10	39±4	1.30	1.44	1.34	1.48	1.61

LSD = .58 (without M–38(E))

THE LEVEL DITCH SYSTEM OF IRRIGATION AT OAHU SUGAR COMPANY

HANS W. HANSEN[1]

As the cost of labor increased during the 1920's, it was necessary to develop a more efficient system of irrigation. As a result of work done at Oahu Sugar Company and several other plantations, the "modified-orchard" or long line system was adopted as plantation practice. Oahu Sugar Company converted to the new system as soon as possible, using either straight or contour lines, depending on the slope of the land.

In practice, as early as then, a contour map was prepared prior to planting on which the direction of the furrows and all straight and level ditches were located. This plan was then applied as planting proceeded. Furrows were laid straight. A variation in grade of from one to two and a half per cent was permitted. As the slope of the land increased, contour furrows were made, also with a grade variation in order to make them as straight as possible.

Level ditches and wing ditches, separately or in combination, cut across the furrows, so spaced that the furrow length was from 250 to 350 feet. The grade on level ditches was a fall of 0.2 or 0.3 feet per 100 feet.

As a result of this conversion, the performance per man-day for irrigating rose from 1.25 acres to 3.5 acres.

There was little or no change until the late 30's and early 40's when the labor shortage began. Then the herringbone system, using the Waialua type of concrete flume, was adopted for the steep palis.

After World War II, there was again a shortage of labor, coupled with increased wages. It was at this time that the Aiea lands were acquired. The greater part of these lands are decidedly on the steep side. A breakdown of the slope range of Oahu Sugar land is as follows:

	Total	0–5% slope	6–15% slope	Over 15% slope
Acreage	11,869.74	6,884.98	4,528.44	456.32
Per cent	100.00	58.01	38.15	3.84

Within three years, the herringbone system was spread over 4,000 acres. The decision to change over from the level ditch system on the steeper fields was made not only because of labor shortage or a need to increase performance, but also because of defects in the level ditch system which are magnified as the slope of the land increases. The area lost to level ditches as the slope of the land increases

[1] Assistant Manager, Oahu Sugar Company, Ltd.

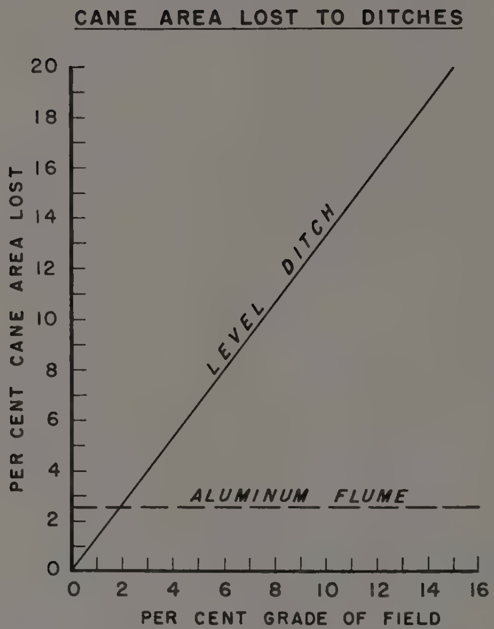


Figure 1. The assumptions on which this curve is based are: level ditch grade, 1½ per cent; level ditch width, 5 feet; no wing ditches. In the system of continuous long line irrigation at Oahu Sugar, discussed later, a fixed 2/58 per cent of the field area is lost to ditches and flumes, regardless of slope, as against an ever-increasing percentage in the regular level ditch system.

is shown in Figure 1. For each one per cent rise in field grade, 1.33 per cent cane area is lost to level dtiches.

Any attempt to keep level ditches further apart on slopes over four per cent, through making more or longer wing ditches, gave additional trouble. Wing ditches on the steeper slopes eroded seriously, which impaired control of water and lowered performance.

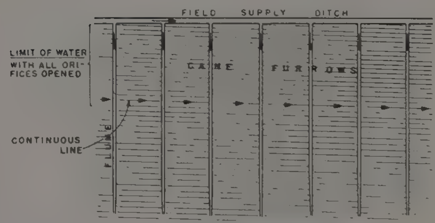
The herringbone system, using the Waialua type of concrete flume, eliminated these defects and made possible a satisfactory performance. Although the herringbone system proved to be quite satisfactory under these conditions, its disadvantages must be recognized. At Oahu these were: first, storm damage during heavy rains through accumulation of rain water in the furrows between the flumes, which results in bursting the furrow banks and serious erosion in the steep slopes; next, the interference with mechanical ratooning and harvesting, which results in high hand-labor costs for field finishing and repairs.

Because of the disadvantages of the herringbone system and the defects of the level ditch system on the steep slopes, the development of the aluminum flume and the continuous long line by Olokele Sugar Company created special interest. This has led to adoption of a system combining level ditches, continuous long lines and the aluminum flume.

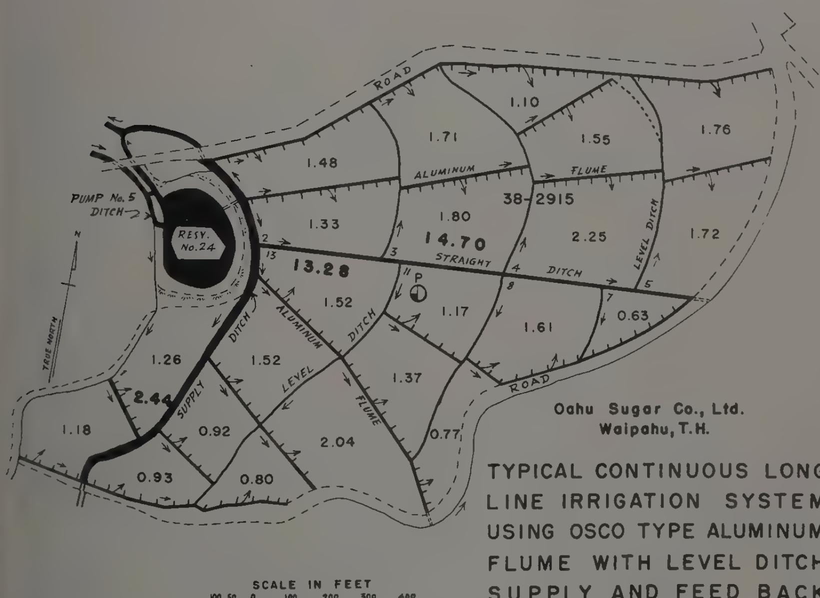
Briefly, layout of the continuous long-line level-ditch system is as follows: furrows are continuous on a uniform grade and slope toward the straight ditch which supplies the level ditch feeding the flumes. The level ditches are spaced 400 to 500 feet apart.

SEMI-AUTOMATIC CONTINUOUS LONG LINE SYSTEM
USING IN-FIELD SUPPLY DITCHES TO FLUMES
IRRIGATING CONTINUOUS LINES

Figure 2. At the top is given a schematic comparison of the two systems of continuous long line irrigation. Above, supply ditches, every 400 to 500 feet, make irrigation almost automatic. In the other system, orifices must be opened and closed as the irrigation water goes down the flumes. Below, a portion of Field 29B is sketched to show the actual layout in field practice.



LONG FLUME LINE SYSTEM
IRRIGATING CONTINUOUS LINES



Oahu Sugar Co., Ltd.
Waipahu, T.H.

TYPICAL CONTINUOUS LONG LINE IRRIGATION SYSTEM USING OSCO TYPE ALUMINUM FLUME WITH LEVEL DITCH SUPPLY AND FEED BACK

PORTION OF FIELD NO. 29B

October 7, 1953

The flumes, laid at right angles to the furrows, are approximately 300 feet apart and are so placed that water running down the furrow may pass under the flume. Two sketches of this type of layout are given in Figure 2.

In practice, sufficient water is fed into the level ditch to supply each flume with enough water so that all orifices in every flume are flowing. In this manner, an irrigator can, and does, handle two level ditches at a time.

Oahu Sugar irrigation practice requires that water be run in each furrow for two to three hours in order to get sufficient penetration. This permits an irrigator to walk the length of his flumes to inspect or adjust the orifices. If water from up-furrow reaches and passes a flume, it continues flowing until it finally falls into the straight ditch and re-enters the irrigation system to be used again. There is no accumulation of water to break furrows and no water wasted by breaking out of fields.

The continuous long-line level-ditch system now covers 300 acres and is scheduled for expansion next year.

Performance has varied from 12 to 20 acres per man-day. The low performance which was obtained in the first field was due to under-engineering the flume and level ditch requirements. In another field, the flume orifices were blocked by limu.

Further details of the system are as follows: in practice, the maximum number of flumes per ditch has been kept to four because it is necessary to limit the size of the ditch and to keep the grade at not more than .3-foot fall per 100 feet; also, during heavy rains, in recumbent cane, a continuous furrow longer than 1200 feet is apt to accumulate more water than it can carry without erosion. Any orifice which lends itself to this type of irrigation will do. However, it may be well to give some data on the flume. The size of the flume is engineered so that sufficient water can be introduced into the flume head to supply a maximum flow for each orifice. The cross section is gradually diminished downstream, maintaining only the size required to carry sufficient water for the remaining orifices.

The orifice is simple. It is a T orifice with the leg of the T pointing upstream. The orifice adjustment is obtained by depressing or raising the slot tabs. The top of the T is dished to scoop water from the flume. The capacity of the orifice, wide open, is 70 gallons per minute, but it can be increased by extending the leg of the T. For lines where hapas exist, either the slot is extended or another T slot is cut for the furrow.

Each outlet is fitted with a diverter to deflect from its downward line of flow the water which, if not diverted, would erode the furrow bank. The diverter also spreads the water in a broad stream in the furrow bottom.

Now, as to the advantage of this system over a continuous long line system which has long flumes and orifices which must be opened and closed: it is almost automatic. If all gates in the straight and level ditches are properly set, water can continue to run indefinitely without serious damage to the field, and runoff can be collected and re-used. The only loss is through over-irrigation. One afternoon, in order to test this, an irrigation overseer set a series of gates and permitted the full flow of water being used by an irrigator to continue flowing all night. By morning, an area equal to that which had been irrigated the previous day had been completed and there was no damage to the field. In almost the same manner, storm damage is eliminated and storm water either saved or safely disposed of if not needed. Less flume material is needed per acre inasmuch as only the head of the flume carries the full flow of water. As the water passes down the flume, each orifice takes its share and the remaining flow requires a progressively smaller flume section.

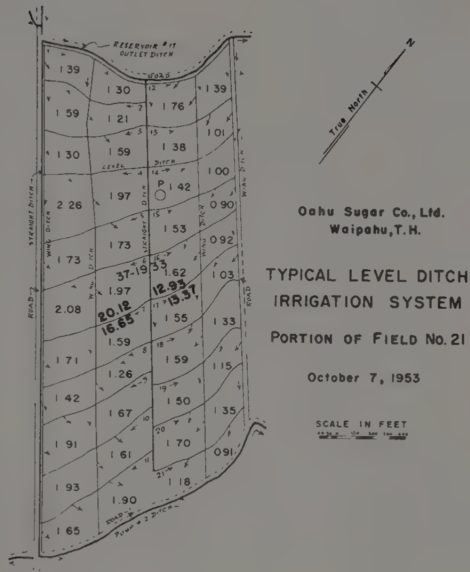


Figure 3. All furrows slope back toward the straight ditch, as in the continuous long line system, with wing ditches used where aluminum flume could replace them.

There are admittedly some disadvantages. First, there is some seepage in the level ditches. Second, there is the loss of land used for these ditches. These losses are greater than for the herringbone system, but are small compared to a regular level ditch system. This is illustrated in Figure 1.

Further, a comparison with the herringbone system brings out these definite advantages: first, it is easy to handle, install and remove; second, harvest operations are not impeded when flumes are removed; third, machine ratooning is facilitated, which does away with a great portion of hand labor for field finishing; and fourth, storm damage is eliminated.

Oahu Sugar still has slightly over 7000 acres in the regular long line system. During the past three years, some definite changes have been made in the layout. Now, all furrows are sloped toward the straight ditch as in the continuous long line system. Fields of four per cent and less are using wing ditches as if they were irrigation flumes. This is not desirable but it saves level ditches, and on slopes of four per cent and less, the damage is not too serious. Another reason is that with this type of layout, it is possible at any time after harvesting to ratoon through the wing ditches, eliminate every other level ditch, lay irrigation flume and convert to the continuous long line system.

As an example of this system, a portion of Field 21 is illustrated in Figure 3.

Performance data for regular long-line level-ditch irrigation since 1948 are as follows:

	1948	1949	1950	1951	1952	To date 1953
Acres per man-day	4.8	5.6	6.3	6.2	6.6	6.7

To summarize, Oahu Sugar Company, for the reasons presented, favors the level-ditch, short-flume, continuous long line system. No claim is made that it is either the best or the ultimate irrigation system. Many problems remain to be solved, and Oahu Sugar Company remains open-minded and willing to adopt any changes which will improve the system.

THE HERRINGBONE SYSTEM OF IRRIGATION

WALTER P. NAQUIN, JR.[1]

Unrest in irrigation circles during the early 1920's is clearly evident in the literature of that day (1) (2). This stemmed from general dissatisfaction with the standard Hawaiian contour system of irrigation, and many new methods were tried in those years.

The herringbone system, so called because of its diagrammatic resemblance to a stripped fish bone, was originated and applied to sugar cane agriculture by H. W. Baldwin (3). He conceived the idea of irrigating contour cane furrows, 150 to 200 feet long, from both sides of a wooden irrigation flume. Mr. Baldwin's idea of a herringbone system was similar to the actual operation as it is today. He wrote: "The water will then flow into all rows automatically and the attendant will have only to patrol the flumes to see that none of the outlets are obstructed and to inspect the ends of the rows to be sure that the water has reached the ends and had ample time to spread laterally before the water is turned off. Thus, it should be possible for one man to irrigate a whole field in a day if there is sufficient volume of water available." The herringbone system has not been automatic. It has, in fact, required careful supervision. But it is interesting to note that the concept of automatic furrow irrigation was mentioned in the literature of 1922.

Other irrigation systems of interest in the 1920's were: the Hawi overhead system; the Ewa border method, or flooding system; the single long line systems, orchard and herringbone; Hawaiian contour systems with attendant modifications familiar to those in the industry, such as the Koloa system, the two-way come-and-go system, the cut line or huli system. With modification in techniques, nearly all of these have survived and may be seen on one plantation or another today.

Waialua experimented with herringbone irrigation and tried various materials for flume manufacture, including tarred burlap and roofing paper. Concrete flume, with galvanized scoops that were suitable both for removing the water from the flume and as gates to close the furrow opening, seemed to be the most satisfactory. In the fall of 1935, John C. Rust, who at that time was the Opaeula division overseer, developed the scoops and openings for a precast concrete flume. The solution of the scoop problem by Mr. Rust, with the help of Herbert Watson and of Manuel Damas in the shops, resulted in a rapid expansion at Waialua of the herringbone layout using concrete flume. Early in 1936, a concrete products plant was completed and by the end of the year, 15 per cent of the plantation had been planted to herringbone layouts. Use of the flume was rapidly expanded until in 1946 it occupied 80.4 per cent of the cane area. (Figure 1) Extension of flume

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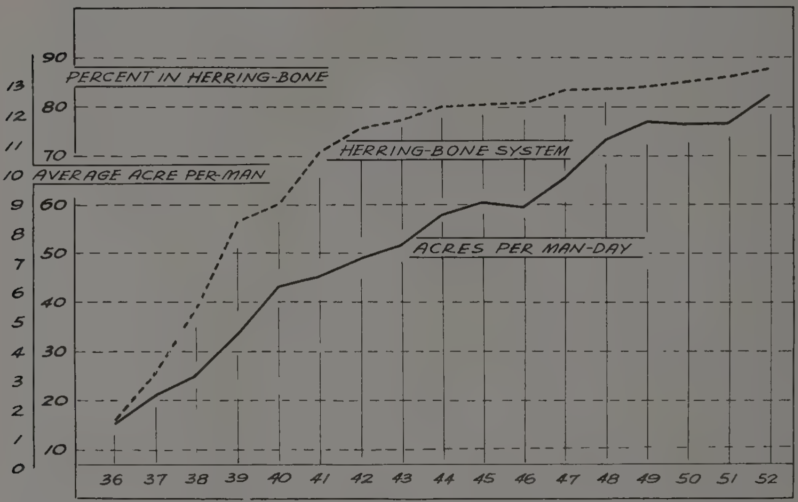


Figure 1. Acres irrigated per man-day at Waialua Agricultural Company, Ltd.

fields has gradually increased since then, and at the present time, 87.6 per cent of Waialua's area is in herringbone irrigation. Use of larger flume has enabled economical installation and high irrigation performance with field grades as little as 0.8 per cent. With the use of flexible harvesting equipment and lighter flume materials, application to even flatter grades requiring the very large sizes may become successful. At the present time, Waialua's flat fields are laid out in straight, long lines in what one might call a modified orchard system of irrigation, using pani pins and opala bundles in the level ditches and concrete pipes with gates at the line heads.

Among the many individuals who have contributed throughout the years to the success of the herringbone system, one should mention H. R. Shaw, (6) (7), who did much of the background work in soil moisture relationships and was actually able to show that high irrigation performance could be obtained along with good irrigation. Louis Vieira, working with Waialua's management team, set the stage for the economical success of the flume and provided the favorable atmosphere along with the checks and balances so necessary for a development of this sort.

After the adoption of the scoop had assured the successful employment of the concrete flume for irrigation, and its installation had become a reality, Waialua slowly built its concept of cane growing around the flume. By 1940, it was apparent that large-sized flume was a necessity for rapid irrigation performance and the 12 x 12-inch flume was standardized for the majority of field areas which, at Waialua, have an average slope of five to six per cent. In 1945, use of the 14 x 14-inch flume was increased and fields were laid out with a standard delivery flow rate of seven million gallons per 24 hours per irrigator (10.831 second feet). As slope and area dictated, flumes as large as 24 x 24 inches were installed at the

headings, 12 x 18 inches on slopes between 1.6 and 2.4 per cent. Full deliveries of water were made to each irrigator until irrigation performance reached 12.76 acres irrigated per eight-hour man-day in 1952.

Today, many individuals in the sugar cane industry feel that an irrigator's performance is limited only by the ability to deliver water to him. If it became desirable, a man using the flume system could handle nearly twice the water that he does today.

Flume line length and area served determine to some extent the size of flume to be installed, but in general, the sizes used for slopes are indicated below:

Field Grade	Flume Used
6% and up	12″ x 12″
4%—6%	12″ x 14″
2.4%—4%	14″ x 14″
1.6%—2.4%	12″ x 18″
Less than 1.6%	24″ x 24″

The Waialua concrete flume is essentially a concrete ditch with 30-inch sections with gates, alternating with 36-inch plain sections. These sections are laid end to end straight down the field grade and the joints are tarred with a special irrigation putty to make them watertight. The openings in the gate sections are closer to one end than they are to the other in order that the section may be reversed as necessary in the field to match wide or narrow furrows. It is generally best to have the gates open about six inches uphill from the center of the cane furrow and about four inches above the bottom.

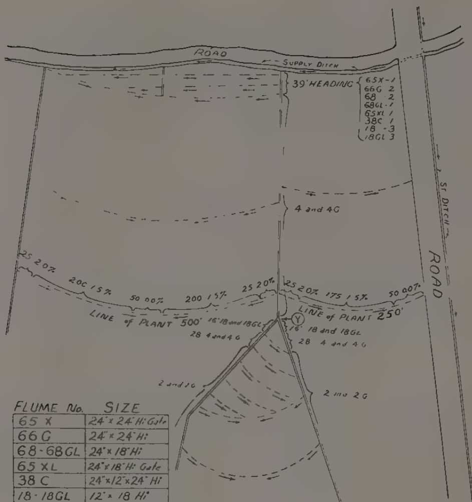
A typical herringbone field layout, in Figure 2, shows the detailed field planning necessary for a successful flume installation. The large flume at the heading near the supply ditch is laid nearly level in order to reach field grade for the full volume of water as soon as practicable. The "X" sections are gate sections; the first closes off the supply ditch when the flume is not irrigating, and the second, near the 38C connector, aids in irrigating the lines ahead of it. The connector is a tapered flume that reduces the 24-inch headings to the 12-inch field-size flumes.

A fairly recent development is the concrete "Y" section for branching the flume. The first "Y" was developed by Tokiji Fujimura in 1945. A precast concrete "Y" was made after a wood model, first installed in Helemano 11, had proved successful. This 18° "Y" section has a tremendous value to the herringbone system and it was rapidly installed in all fields at Waialua during the heavy planting program which spread variety 37–1933 to the greater portion of Waialua's area.

The typical layout shows the planting plan for a 225-foot line. The first 25-foot section is laid out at a two per cent grade in an attempt to reduce over-irrigation at the flumeside and to draw the water away rapidly so that it will not jump the head of the furrow as the cane lodges. The greater portion of the line is laid out at 1.5 per cent with the last 25 feet dead level. We are currently trying out grades of one per cent with a slightly longer level zone.

Before discussing the advantages or disadvantages of the concrete flume, a brief description will be given of its use at Waialua where handicaps have been minimized and where, in some instances, so-called handicaps have proven to be quite beneficial.

Early in the history of irrigation flume at Waialua, it was recognized that the flume system was going to be here a long time. It was the best available method



FLUME No.	SIZE
65 X	24" x 24" Hi Gate
66 G	24" x 24" Hi
68-68GL	24" x 18" Hi
65 XL	24" x 18" Hi Gate
38 C	24" x 12" x 24" Hi
18-18GL	12" x 18 Hi
4-4G	12" x 14" Hi
2-2G	12" x 12" Hi

Figure 2. A typical herringbone field layout at Waialua.

of irrigation, and other operations were gradually developed around its proper use. Perhaps one of the first casualties was mechanical cultivation, because the concrete barriers, set 400 to 450 feet apart along the cane furrow, precluded the successful use of large machinery. Knapsack spraying, with occasional hand weeding, was successfully substituted as an economical and efficient weed control method. Here the solid pathway provided by the flume proved useful to the workers and overseers. Concentrated herbicides could be delivered to the spray gangs, and clean water from a small stream could be rapidly delivered and changed as the gang progressed through a field. As no mechanical equipment entered the field after reshaping, it was possible to inspect the area when it was young and to fix lines sufficiently to guarantee a good irrigation furrow that would last the two years until the next harvest.

Plowing and harrowing operations were next adapted to the obstructions caused by the flumes. Subsoiling and harrowing units were mounted directly on the tractors to provide mobility and a short turning radius. These units can operate right next to a flume line.

Palletizing of flumes for handling by fingerlift and careful selection of hauling equipment have kept handling costs in line and have largely eliminated objections to the weight of the flume.

Grab harvesting, although desirable in its own right from an agricultural standpoint because it causes less soil compaction than other harvesting systems, is better suited to flume irrigation than rake harvesting. In any event, the result of grab-harvesting operations and adequate replanting has been an actual increase in the yields of many ratoon crops as compared to plant crops. Thus, it has not been necessary to move the heavy tonnage of flume for plowing operations in a field oftener than every eight years.

It was necessary and possible to crop away from the pali areas in the winter months because storms can and do cause washouts in the center zones of fields of young cane. The washouts can be minimized by proper cutting of the banks in the vulnerable area. It is annoying and expensive to repair storm damage in younger cane, but it does not preclude an eventual good yield should such damage occur.

The concrete flume has more than justified its use at Waialua through increased irrigation performance. It has reduced seepage losses through the elimination of all straight ditches and level ditches. Once water enters a concrete irrigation flume, it stays confined and controlled by the flume until it is applied to the furrow. It is here that the "Y" comes into prominence, for it replaces the short level ditches and resupply sources that had been necessary to fit the flume to a field. Elimination of these dirt ditch areas, which were weak points in the system, gave irrigators the ability to handle maximum flows of water without danger of a breakdown. Full flumes became the rule rather than the exception. For example, irrigation performance in the Helemano division for the past five years has been over 15 acres per man-day for cane of all ages with an average gross acre-inch application close to six. Data for this division of 2703 acres follow:

	Acres Irrigated per man-day	Acre Inches* applied per acre
1948	17.06	4.98**
1949	14.63	6.22
1950	15.10	6.22
1951	14.50	6.51
1952	15.14	5.94

* WACO irrigation standards require:

1st 5 rounds	3 acre inches per acre
5th to 16th rounds	4 " " " "
16th round and over	5 " " " "

** Figures reported represent gross water delivered to the division and include all ditch, reservoir, and evaporation losses.

It should also be pointed out that the herringbone system has markedly decreased the area devoted to ditches over the plantation. Elimination of straight and level ditches has resulted in a 7 to 14 per cent increase in the area devoted to sugar cane. Along with this saving in area go the pushed observation lines so common where water is difficult to control. In difficult fields under the herringbone system, observation lines may be pushed as close as each 330 feet, but as one looks over the plantation, these pushed lines are the exception rather than the rule. Adequate flume marking techniques, which indicate half-lines and the presence of hapas, have in many cases completely eliminated pushback cane except along the irrigation flume itself. The man-hours required for pushing cane at Waialua are low indeed. Normally, the irrigator does all of the pushing of cane within the 150 to 175 acres to which he is assigned.

Good irrigation supervision has been a necessity with the herringbone system. Flows must be adjusted properly to each line in order that acre-inch applications are sufficient throughout the cane furrow to support the cane plant at the irrigation intervals determined by the moisture-holding capacity and depth of the soil. It is standard practice to run water in each furrow at least one and one-half hours, and generally up to two hours, in order to obtain sufficient lateral penetration at

all points along the cane furrow. The three-quarter zone has presented particular difficulties with the herringbone system and it is true that other areas must be overirrigated in order to prevent stunted cane in this danger area. Controlled applications have largely eliminated this difficulty. It is our thought that a flatter furrow may reduce the time necessary for lateral movement of the water in this poor area and result in an over-all saving in water by reducing the time required to irrigate each furrow. Thirty-eight acres in Kawailoa 18, and 14 acres in Kawailoa 6, have been planted at a one per cent slope to test this theory.

At the present time, irrigation installations at Waialua average 60 flume sections per acre, which amounts to 162 lineal feet of flume per acre. Breakage from all operations at harvest time has averaged between .57 and .75 units (one per cent), which have to be replaced with new flume each two years. The remainder of the concrete flume is left undisturbed, except for small percentages of flume sections which are lifted for the passage of harvesting equipment each two years. It is expected that Tournatwo harvesting operations will result in decreasing percentages of even this small amount of flume movement and replacement.

At Waialua, there are several systems of accomplishing the desired acre-inch applications with the Waialua flume. Fred Krauss, Helemano division overseer, was perhaps the first to demand full flumes of water. These, along with large-sized flumes and the elimination of bottlenecks in the irrigation system, achieved maximum performance consistent with good irrigation. San Kawahara, Kawaihapai-Mokuleia division overseer, has developed and employs a block system of irrigation by which he maintains close control of the irrigation applied. Under the block system, a predetermined number of lines are adjusted to be completed in a given length of time. At the end of the period, all lines are closed and the irrigator moves on to the next block. The size of the blocks is reduced as the cane grows and demands higher acre-inch applications. Kawahara cuts all hapa (half-lines) ahead of the first irrigation and this starts off the first irrigation round in a ratoon field with high performance. The other two division overseers, Bob Jobes, Kawailoa, and Victor Martins, Opaeula, along with Brevard Sinclair, who has recently retired, have obtained equally high performances and excellent yields under the herringbone system of irrigation.

The weak center zone and the tremendous tonnage of material introduced per acre have not proved a bar to the successful employment of the herringbone system on an irrigated plantation of 9694 acres.

Plowing, planting, weeding, and harvesting have been brought into this discussion of the herringbone flume because, in reality, they are the components of the whole concept of the herringbone system.

It is a concept of total agriculture which imaginative management has evolved during the past 17 years to capitalize on the water- and labor-saving potentialities of the concrete flume in developing an agricultural operation that has resulted in maximum production over a long period of years with limited manpower resources and with production costs among the lowest in the industry.

Continual improvement of irrigation methods and practices has been the result of aggressive investigation and work during the years, and the constant emphasis on the practical application of scientific knowledge, as well as the testing of the theories and techniques themselves, will continue to produce changes for the better in the future.

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CONTINUOUS LONG LINE SYSTEM OF IRRIGATION

R. D. GERNER[1]

Although the topic of this discussion is the "continuous long line" system of irrigation, the use of aluminum flumes in field layout will also be included inasmuch as continuous lines are impossible without flumes that can sit on top of the lines in such a manner that water can run beneath them. The term "continuous" is used because one line may be fed by as many as three or four flumes. This is possible because the flumes sit on top of the kuakua and do not impede the flow of water in the line. The term "long line" is applied to this system because one line may run well over a thousand feet.

It should also be understood that no generalized discussion of this nature can take into consideration all of the problems that may arise in laying out and irrigating an area by the continuous long line system of irrigation. An area may present a problem slightly different from that of any other area and, therefore, require a slightly different solution.

FIELD LAYOUT

Fields are laid out by irrigation blocks, the location of which is determined by the location of infield supply ditches. The flumes in each block are supplied by one ditch. The number and location of the infield supply ditches are determined by the topography of the field.

The first step in laying out a typical block is to determine the direction of irrigation by studying the general contour of the area and the location of the supply ditch. Usually the infield supply ditches are more or less permanently located because of the contour of the land and because they may also supply adjoining fields.

A head flume is at the top of the block or at the highest point in the block, as may be seen in Figure 1. The next flume is located by measuring 300 feet at a grade of one per cent from the top of the head flume at point A, the middle of the head flume at point B, and the bottom of the head flume at point C. The flume line is then staked by sighting in these three points, provided the grade of the flume is sufficient for water to run. Other than this, there are few restrictions on the grade of flume, as the aluminum flumes can be rolled to prevent excessive splashing on higher grades.

Successive flume lines within the block are laid out the same way from each preceding flume.

[1] Irrigation Superintendent, Olokele Sugar Company, Ltd.

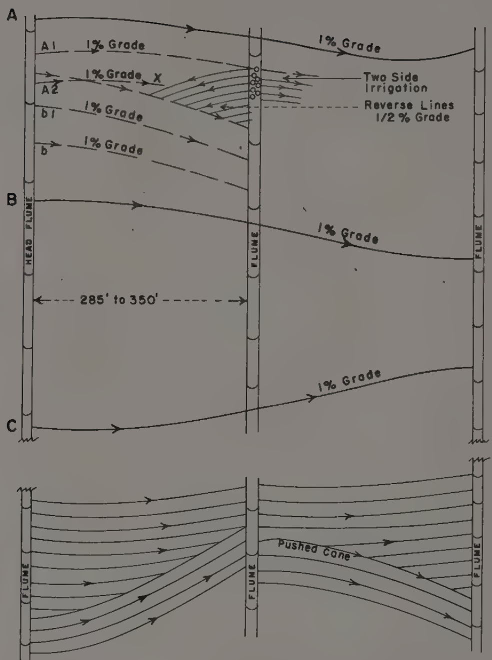

Figure 1. Typical block for continuous long line system of irrigation, including, at lower left and right, details of head and tail hapa furrows.

The next step is to put in pins to guide the planting machine operator in making the irrigation furrows. The first guide line at point A is used as a base. Another guide line 25 feet from point A, at A-1, is measured off parallel to the line from point A, and the grade of line is checked to see that the one per cent grade is maintained.

If the one per cent grade is maintained satisfactorily, another parallel line is pinned off at point A-2.

If the grade increases, as shown in Figure 1, lower left, the line is repinned to maintain the one per cent grade and head hapas are put in to irrigate the unpinned area.

If the line loses grade, a mark at "X" in Figure 1 is made at the point where the grade of line began to change, and a new position 50 feet downgrade from point A-2 at point b is taken and a line of one per cent is pinned in. A further parallel line is put in at point b-1 working upgrade so that in the end, a small triangular space remains unpinned.

To irrigate this small space, it is necessary to reverse the grade of line and irrigate these lines, as well as the regular line, from the next flume. A grade of one-half per cent is maintained on these reverse lines to compensate for their shortness and to insure adequate moisture penetration. The purpose of the re-

verse lines is to eliminate hapa lines and the pushing of cane required to gain access to them; however, 100 per cent elimination is impossible and hapa lines must occasionally be used. In such cases, these hapa lines are supplied by one line, which necessitates pushing the cane only on this one line, as illustrated in Figure 1, lower right. Also, an extra large opening is put on the flume feeding this one line to increase the volume of water.

To fill in the guide pins between succeeding flume lines, this same operation is used.

In general, a distance of 300 feet is maintained between flume lines, and there is no restriction on the maximum grade of the flume beyond the assurance of a flow of water.

The grades of irrigation lines are maintained at one-half to one and one-half per cent.

PERFORMANCE

To give an indication of the man-day performance of the continuous long line system with the Olokele type of aluminum flumes, two sets of data are presented in Table 1.

The performance of the long line system is compared to the performance of the previous system, level ditch, to indicate the percentage of increase in the number of acres irrigated per eight-hour man-day.

The first set of data is a summary of the Monthly Irrigation Report for March, 1953, for both flume and ditch fields for the four sections at Olokele.

Table 1

FLUMES				DITCHES		
Man-days	Acres	Av. Acres per man-day		Man-days	Acres	Av. acres per man-day
50¼	1,018.46	20.27	Section I	84½	756.89	8.96
72¼	1,203.58	16.66	Section II	39	357.67	9.17
89½	1,346.48	15.04	Section III	23½	179.41	7.63
68	1,119.51	16.46	Section IV	82	728.49	8.88
280	4,688.03	16.74	TOTAL	229	2,022.46	8.83

Table 2 presents a comparison of the performance of two average fields for an entire crop, first laid out in level ditch and later laid out in continuous long line with aluminum flumes.

Table 2

	Area	No. of* Irrig. Rounds	Man-days	Acres/8-hr. man-day
Field 50—1951 Crop—Level Ditch	165.30	23	675	5.63
Field 50—1953 Crop—Flume	157.48	37	396.25	14.71
Field 20—1950 Crop—Level Ditch	34.70	27	105.75	8.86
Field 20—1952 Crop—Flume	34.95	29	60.25	16.82

* Rain rounds were excluded because they do not indicate man-day performance.

Provided there is sufficient water, the irrigation performance per man-day in flume fields is consistently higher than the performance in level ditch fields. The reason for this higher performance is that the irrigator is able to irrigate two or three flumes and run water into a greater number of longer lines at the same time.

CONCLUSION

It is felt that the long line system of irrigation as practiced by Olokele is fairly well suited to Olokele's conditions. The soils at Olokele are mostly silt loams which are fairly tight and not easily wetted. This system allows a small amount of water to run very slowly in the line, which gives a greater opportunity for moisture penetration. A high man-day performance is maintained despite this slow movement of water in the line because the system allows the irrigator to irrigate a large number of lines at the same time without losing control of the water.

It is also felt that the continuous long line system permits a fairly uniform distribution of water, which is important because of the increasing number of cultural practices dependent upon irrigation.

A METHOD OF FIELD LAYOUT

WARREN GIBSON[1]

In producing a crop, the irrigator's principal tool is the field layout. With due consideration to all cost factors, he should make it the best tool possible, and should design his layout to meet the following specifications:

1. Proper furrow slopes for the various field conditions of soil type and land slope.
2. Evenness of furrow slope within reasonable limits.
3. Optimum furrow length in relation to furrow slope, land slope and soil type.
4. Adequate drainage.
5. Delivery of the maximum quantity of water that can be regulated properly with a minimum amount of flume and ditch and with no bottlenecks in the system.
6. Minimum number of hapa furrows, short furrows and over-length furrows.
7. Minimum amount of grading.
8. No harvesting, hauling or reshaping bottlenecks.

This is a large order. Probably no field layout will ever completely meet these specifications, but they serve as a target at which the supervisors of Ewa Plantation Company have agreed to shoot.

The preplanning that was done with our old method consisted of a sketch showing the proposed location of flumes and ditches and the general furrow direction. This was submitted to the irrigation supervisors who would suggest changes and give their approval to the general plan. The layout crew located the flumes and ditches in the field and marked the contours. It was then up to the plant machine operator to obtain the correct furrow slopes and locate the hapa and short furrows. This method resulted in some off-slope furrows, too many hapa furrows, and an excessive amount of flume and ditch.

There are two keys to obtaining field layouts which approach the specifications listed. The first key is: those responsible for production of the crop must specify the desired furrow slopes and furrow lengths for each section of the field. Provision for time is the second key. Time is needed to review the weaknesses of the old layout, to prepare alternative layouts, to calculate irrigation performance and installation costs of the various alternatives, to review the alternatives with those who will be using the layout, and to make adjustments in light of suggestions submitted.

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Presented below is an outline of the method developed at Ewa, listing the steps and indicating the timing:

Step 1. Conduct a detailed inventory of the present layout. (At least two years prior to plowing.)

Step 2. Prepare a contour map. (At least two years prior to plowing.)

Step 3. Review present layout with irrigation supervisors for the purpose of revealing present weaknesses and bottlenecks. (Off-season prior to plowing.)

Step 4. Specify desired furrow slope and length for each section of the field. (Off-season prior to plowing.)

Step 5. Prepare alternative layouts. (Off-season prior to plowing.)

Location of flumes and ditches.
Flume sizes and flow data.
Direction and length of furrows.
Location and approximate number of hapa furrows.
Location and approximate number of short and over-length furrows.
Grading requirements.
Drainage provisions.
Inventory of irrigation facilities.

Step 6. Review alternative layouts with supervisors concerned and obtain approval of Field Superintendent. (Off-season prior to plowing.)

Step 7. Prepare final layout map. (Off-season prior to plowing.) In addition to the items listed under Step 5, show the following:

Number of flume pieces required for each flume line by size and type.
Distribution box design for each location.
Number and location of pipe and ditch gates.

Step 8. Install approved field layout, making field changes, if required. (Two or three days ahead of planting.)

Step 9. Conduct a detailed inventory of the new layout. (Off-season following planting.)

Step 10. Follow up. Review layout and results with supervisors concerned, recording pertinent data. (Periodically)

During the off-season, alternative layouts are prepared from contour maps by the field layout man. The first step is to locate continuous furrows on the desired slope. Colored pencils are used: green for one direction and red for the opposite direction. Flumes, ditches and every fifth furrow are then located. A trial and error procedure is used to obtain the best layout. In almost every case, the first attempt has been improved by additional trials. To illustrate, the field layout man once submitted a proposed layout for a 64-acre section which appeared satisfactory, but, at the suggestion of an irrigation supervisor, he tried a different approach. The resulting plan reduced the flume and ditch by approximately 3900 feet in comparison with the old layout and approximately 3100 feet in comparison with the previously proposed layout.

Space does not permit a detailed description of the installation procedure, Step 8. The principal difference between the procedure developed and past practice is that the predetermined location of key cane furrows is transferred

from a map to the field rather than marking the contours and leaving it up to the plant machine operator to establish the furrow location. After the key furrows are transferred from the map to the field, the slope of each is checked and, if required, changed. In practice, very few changes have been necessary. A plane table has proved to be an effective instrument for this purpose but is not a requirement. The procedure has proved satisfactory both on exceedingly flat lands and on lands with slopes up to approximately 20 per cent.

Development of this layout method necessitated the defining of areas of responsibility. Specifying the optimum furrow slopes and lengths is a function of those responsible for producing the crop: the Field Department. Preparation of alternative layouts is an engineering function. The Field Department is responsible for final approval of the preplanned layout. Actual layout installation (surveying, not installing flume, etc.) is an engineering responsibility. Ewa's organization places line responsibility for field layout with the Preparation Division, a part of the Field Department. The Civil Engineering Department performs the service function of preparing contour maps. The Industrial Engineering Department supervises the preparation of alternative layouts, prepares cost comparisons and maintains necessary records.

Effectiveness of the layout can quite readily be evaluated by observing such measurable factors as furrow slopes and lengths installed, water penetration, irrigation performance, flume capacities, amount of flume and ditch installed, and installation costs. Water flow in the furrows and the effectiveness of drainage provisions can also be observed. Opinions of the men close to the operation should not be overlooked as a means of evaluation. During the application of first water, ask the irrigators and their first-line supervisors how they like the layout. Perhaps answers to this question would be a good index as to whether your present layout method is satisfactory or in need of overhaul.

Ewa's results with the new method of layout have been quite satisfactory. Errors have been made, but it is believed that experience and training are the answers to preventing future errors. The amount of ditch and flume has been reduced in most fields. In one field of 213 acres, the reduction amounted to approximately 6300 feet of flume and ditch. For those fields in which additional flume and ditch were used, the reasons were known and carefully weighed several months before actual installation. Probably the most important improvement has been in obtaining the desired furrow slope. The number of hapa furrows has been considerably reduced; none are installed without the consent of the irrigation supervisors. The irrigators and their supervisors have generally expressed satisfaction with the layouts. These results have been obtained without increasing costs of layout preparation and surveying.

RECENT DEVELOPMENTS IN IRRIGATION FLUME

R. L. Wold[1]

Now gaining in popularity in the Hawaiian sugar industry is a new layout and method of irrigation generally referred to as the continuous long line system. In this system, the cane lines run at a predetermined grade across the entire width of a field. Frequently, a field may be so wide that the lines must be broken by a safety spillway drain. Severe rainstorms and highly erosive soils will help determine the maximum advisable length. At present at Lihue, 2000 feet is considered maximum. To supply water to the cane, flumes cross the fields at approximately a right angle to the cane lines. Various outlets, scoops and similar devices are used to allow the water to pass from the flume into the cane line. As more work is done on the problems of water metering and transfer, many improvements on present devices will undoubtedly be made.

In order to secure the best results with the continuous long line system of irrigation, certain problems must be met and solved. Some of these are:

1. Adequate sources and facilities for water (culverts, siphons, ditches, etc.)
2. Selecting flume and outlet. Since the purpose of this paper is to discuss recent developments in flumes and outlet devices, major emphasis will be given to the work done by the various plantations during the past few years.
3. Field planning and layout (kind, direction, and slope of line, ditch and flume locations.)
4. Planting (locating hapas; uniform and accurate slope of line; inter-relationship of flume spacing, slope of line, soil porosity, and rate of discharge per line.)
5. Installing the flume:
   (a) Handling the flume
   (b) Installing headers and straight ditch gates—selection of type to use
   (c) Digging the flume bed
   (d) Installing the flume and outlets
   (e) Bedding and staking
6. Irrigating with flumes:
   (a) First and second irrigation rounds
   (b) Subsequent irrigations
   (c) Timing of gate closing—overlapping irrigating
   (d) Rate of application, gallons per minute of discharge into line
   (e) Number of flume lines operating simultaneously
   (f) Frequency of irrigation applications—means of determining
7. Keeping flume line clear:
   (a) Removing seed from under and on one side of the flume
   (b) First pushback
   (c) Subsequent pushback

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8. Removing the flume for harvesting
9. Reinstalling the flume after harvesting

FLUME MATERIALS

Metals: Galvanized sheet iron and aluminum are the two metals that have been used as flume materials up to the present time. The first installations at Olokele, using galvanized sheet iron, 24-gauge "Cupraloy M 45," have been in service for about eight years with no protective coating. Recent reports show that this material is badly corroded. At Lihue, 26-gauge galvanized sheet iron flumes have been in service for six years without protective coating. While some deterioration is evident, it is not serious.

If galvanized sheet iron is to be used, it should probably be of "seal of quality" grade; i.e., two ounces of zinc per square foot. Thickness of either 28- or 30-gauge appears to be ample. A coat of galvanized paint every five or six years should prove economical.

The aluminum used for flumes is made by Kaiser. The specifications are 50 SH 34 or 36, Clad. Thickness is generally .032 inch, but some of .025 inch thickness has been used at Lihue.

A section of 52 S ½ H Alcoa aluminum has been in service for approximately six years, with no protective paint. It shows no corrosion, a slight discoloration being the only sign of age. Present practice on most plantations, however, calls for painting at least the underside with a bitumastic type of paint. Preference on Kauai is "Ebinol" paint, cut at the rate of three parts Ebinol to two parts reducer. The paint is normally sprayed on with a hand knapsack. Tests comparing it with other paints are in progress.

Non-Metals: For the older types of flumes, such as the Waialua flume and Pioneer pipe, cement aggregate has been the material most widely used. It has two major disadvantages: it is heavy, and it breaks fairly easily. The relative weights per acre of cement and aluminum would be from 8000 to 12,000 pounds for cement and 175 to 250 pounds for aluminum.

A strong, light cement mixture, which will reduce the high weight, may be available some day. Bagasse, or other plentiful and cheap materials, may be useful in such a mixture. The ideal would be a cheap, expendible flume that could be left in the field at the end of each crop.

Ewa has perhaps done more experimentation with "Panelyte" materials for flume than any other plantation. Panelyte is a laminated combination of wood fiber and plastic. It offers possibilities, especially where corrosion of aluminum might become a problem. Whether it is cheaper and more desirable than aluminum is still an open question. No attempt will be made in this paper to resolve the problem of the cheapest and best flume material. Only much research and time can do that.

A laminated glass fiber and plastic material has recently come into the race. Although it will evidently cost more than either aluminum or Panelyte, it may have a longer life expectancy. It remains to be tested.

STRAIGHT DITCH AND HEADER GATES

H C & S has developed a leakproof, wooden, straight ditch gate that looks promising. It has the following desirable features: a beveled contact face on both

gate and frame; shiplap joints between the boards; and a rubber gasket under the gate.

Several plantations are using precast cement slab framework and a metal gate for their straight ditch gates. The complete discussion of each type and its merits is outside the scope of this paper.

A good straight ditch gate should have the following features: it should not cost more than $15, less if possible; it should be durable enough to last through at least three crops; it should be easy to install; it should be large enough to dam the water properly for diversion into the flume; and it should be leakproof when closed. In addition, the gate should be protected from water erosion and should be easy to adjust in controlling the flow of water.

The flume header gates are normally made of wood. The important specification is to make them as wide as necessary, with the bottom as nearly flat as possible. Lihue has found it satisfactory to round one bottom corner of two pieces of 1 x 6-inch board so that the width of a flume header can be increased or decreased by sliding the boards out or in, leaving the corners round, but the bottom flat.

Olokele developed a novel feature by nailing two strips of aluminum to the flume header gate. The flume header is then inserted between them, thus making it unnecessary to nail the header flume directly to the header gate. Lihue is incorporating the leakproof features of the H C & S gate into this header gate.

DESIGN OF FLUME, OUTLETS AND ACCESSORIES

Several flume outlets are giving satisfactory service in the industry at the present time. The main ones are:

1. Olokele—2-inch hole. Stopper closed from below.
2. Wailuku—4-inch round with grommet and sock. (Also being used and developed at H C & S, Ewa and other plantations.)
3. Waipahu—"T" slot. 3x3-inch T cut, no closing means.
4. Kekaha—"U" slot. Modification of "T" slot, no closing means.
5. Lihue—1⅜x4-inch rectangular hole. Tabbed and ski-jump closing for level and steep slopes.
6. University of Hawaii—a round can in a grommet-lined hole.

As a review of the requirements of a good flume outlet, let us look first at the basic qualifications of an ideal outlet.

1. It should be simple and inexpensive to construct, costing not more than 15 cents apiece, or between $5 and $6 per acre.
2. It should be adjustable from zero flow to a maximum of about 100 gallons per minute in a continuous curve, in steps of 25 gallons per minute.
3. It should be easily opened and closed and leakproof when closed.
4. It should be so fashioned that the adjustment of flow rate is easy and simple.
5. It should be easy to attach or remove whenever necessary, and should have no protuberances to obstruct nesting or moving the flume sections.

6. It must be as durable as the flume.
7. It should not be easily clogged by rubbish; if clogged, it should be easy to clean.
8. It should have baffles to reduce discharge velocity on steep slopes in erosive soils.

It is difficult to find an outlet filling all of these requirements. However, progress is being made. With so much study devoted to this problem, improvement is certain.

A test was run to determine the rates of discharge possible with the various outlets in use at the present time. The measuring means was a calibrated three-inch rectangular weir installed under the flume. The following results were obtained:

Flume	Size and Type of Outlet	Field 28-L 8/6/53 2% Grade Gals./Min.	Field W-2 8/12/53 7½% Grade Gals./Min.
Olokele	Standard 2″ Round	34	38
	Raised blister	48	51
Waipahu	"T" Slot (Standard)	38	41
	"T" Slot with beer can deflector	34	no test
	"T" Maximum open	75	71
	"T" Maximum with beer can	63	no test
Wailuku	4″ Round (Sock)	88	111
Lihue	1⅜ x 4″ Rectangular tab—Standard	75	75
	1⅜ x 4″ Rectangular tab—Raised blister	101	106

No tests have been run as yet with "U" slot being tried at Kekaha.

OLOKELE FLUME AND OUTLET: This flume and outlet are being used on the largest acreage of any of the new flumes at the present time. An estimate of total area at Olokele and other plantations would be about 4000 acres.

The outlet is a round hole, two inches in diameter, with a round block of wood fastened to a wooden cross member used as a stopper. Larger holes can be used if larger volumes of water are needed. On top of the stopper is a gasket which serves as a seal when the plug is pulled up against the underside of the opening. Two flexible, galvanized tie wires, one on each end of the wooden cross member, serve to attach the outlet stopper to the flume. A shorter block is used for the tubed flumes than for the open ones. A blister on the downstream side of the hole serves to catch and divert the water through the flume bottom. By turning the wooden base block, adjustment of the flow and deflection of the discharge stream are possible. The Olokele method matches outlet to cane line by means of a series of about seven hole patterns on a 10-foot flume.

WAILUKU FLUME AND OUTLET: The largest area on which this flume is installed is at Wailuku and at H C & S on Maui. It covers approximately 3000 acres of land at the present time. Some of this flume, with modifications, is installed at Ewa, using Panelyte. The major difficulty has been finding a cheap and durable material for the socks. Recent developments have brought to light a rubber product that appears to be far superior to any thing tried so far.

With the Wailuku flume, the problem of matching outlets to cane line has been solved by using standard punched flumes with spacer blanks between them.

WAIPAHU "T" SLOT AND KEKAHA "U" SLOT: Flumes with two types of openings are being extensively tested at Oahu Sugar and Kekaha. The first is composed of two slits in the bottom of the flume, cut in the shape of a T. The cross of the T is slightly raised as a blister, and the two flaps, made by the stem of the T, bend downward as flow adjustment for the flume. With the T slot, no means for closing the flume opening is provided. The principle of operation is to plan and lay out the field in such a way that the flume lines will be short enough to permit irrigating all of the cane lines on one flume line at the same time.

The U slot is similar to the T slot in that no closing means is used. A "U" shape is cut, and the outlets are matched to cane lines by means of blank spacers. Tests are being conducted at Kekaha to determine whether or not the outlets can be punched in the flume after it has been placed in the field.

LIHUE TABBED AND SKI-JUMP OUTLET: This flume occupies approximately 800 acres at Lihue, Grove Farm, Pioneer and Waimea plantations. There are four $1\frac{3}{8}$ by 4-inch rectangular holes equally spaced at 30-inch intervals in each $10\frac{1}{2}$-foot flume, and because the holes are standardized, the matching of one outlet to each line is assured. No matter at what angle the flume crosses the lines or where hapas come in, an outlet can be found near enough to discharge into any line.

On slopes with a grade of less than 10 per cent, water flow is against the blisters. A tab is attached to the flume on the upstream side of the outlet. This $4\frac{1}{2}$ by 5-inch piece of flexible rubber is fastened at one edge only; the free edge lies over the flume opening on top of the blister, thus closing the opening. To release water, the free end of the rubber flap is depressed through the flume opening by means of a quarter-inch rod, 30 inches long. In closing the outlet, a hook at the end of the rod engages the free end of the flap and flips it back on top of the blister. The weight and pressure of the water serves as a seal.

At present, the tab is attached by means of glue; Minnesota Mining Co.'s glue No. EC 1022 has been found best for this use. However, it is planned to cut a slot one inch back from the edge of the outlet hole, inserting a precut tab prior to rolling the flume. Tests of this method indicate that the tab is held much more securely than by glue.

For slopes of greater than 10 per cent, the flume is tubed and the flow of water is with the blisters. On these slopes, the outlets do not need tabs. The velocity of the water causes it to "ski-jump" the openings without leaking.

In order to remove water from the flume, various scoop designs have been used successfully. The present scoop is a slightly V-shaped piece of aluminum, with sides. It is inserted into the outlet from which water is to be taken and diverts the flow back uphill which tends to baffle it somewhat. The scoop is held in place by a small wire, which passes through the top of the scoop, then through the flume and back into the scoop.

To supplement flow in a cane line, usually in order to feed hapa lines, the "rattrap" type of scoop has been used. This scoop has a spring on its back, and lower sides than those on the V scoop. It discharges water slightly downhill; so, if it is placed on the uphill outlet and a V scoop is placed on the downhill outlet, a converging flow of about 200 gallons per minute can be secured. (Figure 1)

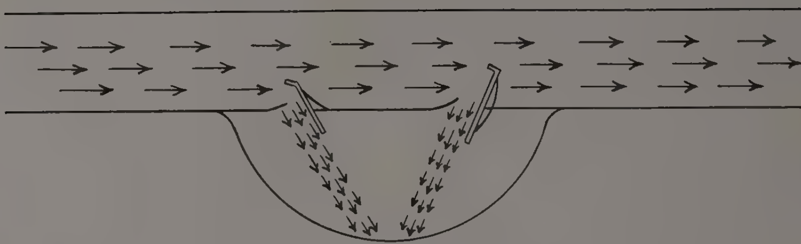

Figure 1. To supplement flow of water from aluminum flumes at Lihue, two types of scoop are used simultaneously, the rattrap, shown at the left, and the V-scoop, shown at the right.

PRESENT EXPERIMENTAL WORK AT LIHUE: At present, some experimental work is being done on outlet devices for flumes made of materials other than metal which can be blistered. The two approaches under study are: (1) insert blister; (2) tilt-periscope.

In the first of these, a standard Lihue outlet hole and blister have been formed in a piece of metal. This blister and tab are then fitted into a large rectangular hole in the flume proper, whether made of cement, Panelyte, laminated glass fiber or other material.

The second is a combination tilt-periscope scoop that works in a rectangular hole in the flume. To open the outlet, the body of the scoop is tilted uphill, thus causing the water to flow in under the forward lip of the scoop. To increase or decrease the flow rate, the scoop can be lifted up or pushed down into the flume. A rubber gasket on top of the scoop aids in making the opening water-tight when the scoop is closed.

In order to improve ease of flume installation and to achieve a more leak-proof flume joint, tests are under way on a tapered, slip-joint arrangement. For the open type of flume, both edges of the flume are turned inward. The ends of the downstream edges are tapered so that they can be fitted under the inward lock seams. No wires or straps around the flume are necessary; a cross brace that lugs under each of the lock seams is sufficient.

In conclusion, it might be stated that although progress on new flumes and flume outlets is gratifying, much remains to be done. As a spur to the workers on this phase of irrigation, a few of the problems that still exist and on which more work needs to be done are listed:

1. Improved method of securing accurate grade of lines.
2. Improved means of feeding hapa lines.
   a. Possibility of increasing widths of cane lines in order to eliminate hapas wherever possible.
   b. Expendible tubes to feed the hapas.
   c. Olokele's method of reverse irrigation.
3. Mechanical means to dig and install headers and straight ditch gates.
4. Mechanical means to dig and lay flume.
5. Improved means to open field for harvest and to remove flume.
   a. Expendible flumes—no need to remove.

6. "Y" flume for splitting the water.
7. Easy and effective means of staking aluminum flumes.
8. Mechanical means of handling and transporting flumes.
9. Basic data on penetration in various soils as related to rates of flume discharge and grade of line for determining flume spacing. These studies to be made in cane of various ages to note effect on water movement and penetration of cane stools, trash, etc.
10. Test for ideal cultural practices for best water use and for best mechanical harvesting.

BACKGROUND AND RESULTS OF RECENT IRRIGATION TIMING TESTS IN AMERICAN FACTORS PLANTATIONS

G. YUAN EWART[1]

INTRODUCTION

Experimentation on irrigation intervals is not new to the Hawaiian sugar industry. A brief review of irrigation tests is given by Wadsworth in an index of literature on irrigation investigations in Hawaii during the past three-quarter century (15). That the quest for better techniques for timing irrigation rounds and for determining water requirements had not been completed at the end of his chronological listing (1882–1948) is made clear in his conclusion: "The simple request for more information on methods of irrigation and desirable irrigation intervals which was made in 1882 is still valid and continues to act as the spark for present studies as it has in the past. The economic pattern has changed; our knowledge of the effects of water upon cane growth has increased; new tools are available. But the basic questions of 'how' to irrigate and how often cane should be irrigated are still current."

The emphasis and technique of early irrigation timing tests were invariably conditioned by the soil moisture concepts current at the time, as well as by the inconsistencies inherent in the basic philosophy of field trials. Obviously, the type of generalized 'yes' or 'no' answer hoped for by the industry could never be found because it would have to be based on the assumption that data, in order to be valid, must be true for all plantations at all times. As long as irrigation, fertilization and ripening requirements are tied to such yardsticks as an interval of a set number of days, a set number of pounds per acre, and a set number of days for withholding water before harvesting, no plantation can give an answer which is valid for another plantation dealing with different soil conditions. Furthermore, one's own results may be refuted the next year when different weather conditions prevail.

Experimental data should be considered valid only for the specific set of conditions or for the test environment concerned. Soil and weather effects are certainly two of the most important determinants to consider in evaluating, classifying, and applying the results from any agronomic test. Soils on plantations should always be referred to by soil type and soil family. Results from tests conducted in a given soil type should only be applied to areas of similar soil types. Finally, yardsticks should be tied to the growth requirement of the cane and to the in-

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herent supplying capacities of the soil concerned, rather than to an inflexible fixed-day or fixed-pound approach. Present day research workers in the sugar cane industry are more fortunate than their predecessors, because soil maps of the Hawaiian Islands, completed by Cline (5) in 1947, are available. In irrigation studies, new concepts in soil physics make it possible to give a simple interpretation to soil moisture regardless of texture, the reference, of course, being to the potential energy concept by Buckingham (1) and the thermodynamic free energy concept of soil moisture developed by Schofield (13) and Edelfsen and Anderson (6). New techniques developed by Richards, et al, (11) (12), enable us to use the soil moisture tension approach as a means of expressing the moisture retained by soil throughout the whole range of moisture extraction by plants. The Experiment Station, HSPA, has been using these techniques to prepare moisture retention curves for many interested plantations.

Analyses of plant tissue and soil during the crop cycle have recently led to the acceptance of the principle of replenishment based on crop demand and soil supply in preference to the static recommendations of field trials which disregard changing rates of demand and supply as functions of changes in space and time. This is not to infer that plot testing has little value. It is a very necessary technique in measuring and evaluating recommendations obtained by the demand and supply approach.

Since the stage has been set for proper evaluation of techniques in irrigation control, systematic effort on the part of the industry in testing these techniques should do much to answer the request made by Whitney (14) in 1882 for information as to how often cane should be irrigated. The systematic approach would be:

1. Survey available techniques and equipment. Study reports published by research workers outside of Hawaii covering their experiences with the various types of instrument, and select those which promise satisfactory performance under Hawaiian types of soil (mainly kaolinite and montmorillonite clays) and plantation cropping conditions.

2. Conduct tests of the selected instruments, starting on small plots and extending to large acreage testing. Follow with special tests to measure and compare the seriousness of the recognized shortcomings of the most practical instruments.

3. Develop and improve techniques for interpretative recording of data on a field scale, with emphasis on the relationship of irrigation index to soil type. Test these techniques in representative fields to eliminate difficulties not uncovered during the small plot tests, and to demonstrate their feasibility and value in terms of monetary savings for the whole industry.

The first step was undertaken in 1948 and 1949, and the results are summarized by Ewart (7). The next step was also reported by Ewart (8) (9) (10). Three Grade A tests were harvested in 1952, one at Kekaha, one at Oahu Sugar, and the third, made jointly by the Station and Waialua at that plantation. In addition, the yield data given in Table I were obtained in 1952 from seven representative fields in Kekaha (4 makai, 3 mauka), covering three soil types (low humic latosol —N1, N2; gray hydromorphic clay—H3, and intrazonal dark magnesium clay—M) from three 1951 and four 1952 crop fields. In the three Grade A tests, irrigation control for low humic latosols at 5000 ohms resulted in no difference in yields when

compared to field practice, but demonstrated significant savings in irrigation. Similar results were obtained on a field scale in the three main soil types at Kekaha Sugar Company.

EXPERIMENTAL DESIGN

The objectives of a coordinated irrigation test were defined and the experimental design was selected after a series of meetings between members of the Experiment Station, HSPA, and plantation personnel of American Factors, Ltd. The objective was to evaluate irrigation control using Bouyoucos blocks and tensiometers in comparison with whatever plantation practice was then current in timing irrigation rounds. The test was confined to low humic latosols and the general index recommended was 5000 ohms for blocks and 0.25 atmosphere tension for tensiometers.[2] For observational purposes, a high soil moisture stress treatment of 50,000 ohms was included. This would represent the dry extreme while the tensiometer irrigation at 0.25 atm. would represent the wet extreme. Irrigating at 5000 ohms in low humic latosol (normal phase) would represent moisture replenishment when approximately two-thirds of the available supply has been used up where the available moisture range is taken as the difference between the one-third atmosphere percentage and the 15 atm. percentage.

The design includes seven replications of each treatment in plots of sufficiently large size to permit normal irrigation applications. A test area averaging 13.5 acres was used in each plantation. A 30 x 30-foot area, marked off in the center of each treatment plot, was harvested at the end of the test for yield comparisons.

As an additional feature, six gypsum blocks were placed at six-inch intervals below the bottom of the furrow to measure profile soil moisture tension gradients. Two blocks were installed in each plot under the supervision of the Experiment Station, HSPA. In addition to the tensiometers which were installed in the high moisture level plots, one tensiometer was installed for observational purposes in a single replication of the lower moisture level plots.

Root developments of matured cane in the selected experiment areas were studied prior to the test, and wherever conflict between Clement's standard tensiometer installation at two feet deep and the actual root zone was found, the instruments were installed at the depth most representative of the lower portion of the zone of root concentration. This is essential as the main consideration is measurement of moisture depletion and supply directly in the soil moisture reservoir of the root zone, and not at an arbitrary depth unrelated to root mass location and to the variations in profile characteristics which influence root development.

Special precautions were taken to prevent water in an irrigated plot from entering another treatment plot not due for irrigation. The blocks themselves indicated whether or not lateral seepage or breaks in lines caused irregular watering.

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[2] Waterhouse (16) reported that tensiometers were located in the root zone, and that tensiometer readings of 25 were used to regulate irrigation timing operations. He further observed that irrigating at a reading of 15 was more desirable during the first year. Clements (2) (3) recommended irrigation at tensiometer readings of 25 without reference to soil types, and at a set two-foot depth which he emphasized as the most representative root zone depth in all "except perhaps a few shallow soils." Ewart (9) suggested using blocks and irrigating when two-thirds of available soil moisture has been used up. This may range from approximately 2000 ohms in the more eroded, gravelly, open soils and the mildly saline soils, to 5000 ohms for low humic latosols (normal phases), and to as high as 30,000 ohms for the hydromorphic montmorillonite clays.

Before starting any moisture differential treatments, it was decided to wait until the crop was three to four months old and had been fertilized. This decision was made because the moisture requirement at planting is separate and distinct from the requirement of plant roots and from extraction of moisture from the soil per se.

Readings were taken as frequently as possible to enable the closest possible adherence to average treatment index. Levels of soil moisture vary from area to area within a field at any given time due to variations in topography, in rockiness, in depth of top soil (result of grading), in application of water, in drainage characteristics, in compaction, and in location in the field, whether windward or leeward. The only way to minimize these differences would be to take readings of all plots several times a day, irrigating each plot individually at the time its index reading indicated. To do this with over 20 plots is not economically practical; even if it were, the perfectionist would wonder whether the station location gives a sufficiently accurate picture of average moisture level for the entire plot. It is obvious that experimental technique must not deviate from the routine followed under field practice to such an extent that results will have little application to field practice. Hence, readings from the seven plots in each treatment were averaged and water was applied when the average reading equalled the treatment index. One cannot help wondering whether the consistently wetter plots within each treatment would not give higher yields than plots which actually underwent a drier regime than that called for by the average treatment index. It was possible, however, when the test was completed, to find the answer by recombining all plots on the basis of actual treatment received, irrespective of the classification to which each belonged. This recombination of Kekaha data is shown in Table II.

Table III summarizes the general characteristics of each test location. It is regrettable that this paper was prepared before sufficient data could be collected on the Pioneer test to warrant its inclusion in the cost comparison. However, several serious discrepancies invalidated the B treatment in the test. One of these was the fact that the irrigation index used was more consistently 20,000 ohms than 5000 ohms, round after round, from the start of treatments until the cane was 14 months of age. Hence, the B treatment became 20,000 ohms rather than 5000 ohms, and averaging these yield results with the B results from the other three plantations would certainly not be valid.

DISCUSSION AND SUMMARIZATION

Table IV lists the test results for each treatment as well as the irrigation requirements at each of three plantations.

Several basic concepts or relationships pertinent to a better understanding both of irrigation economics and of the significance of the results from these tests should be discussed.

1. Evaluating field performance in terms of dollars and cents

The sugar industry is certainly not in business to produce the most cane per acre. Nor is it even in the business of producing the most sugar per acre irrespective of cost. Yet sometimes agriculturists tend to emphasize an increase in yields with too little regard for a more realistic evaluation based on dollars and cents. Their business is solely to produce profits, and the measure of the desirability of

any change in agronomic practice is the increase in the net crop value or income per acre resulting from it. Irrigation is the highest cost item in raising a sugar cane crop and an irrigation control program is efficient only if it results in a higher net income per acre. An increase in expenditure is not justified even if it results in an increase in cane yield unless the increase in crop value more than makes up for the increased cost of production.

Table V shows that for normal low humic latosol soils, irrigation control by blocks at 5000 ohms resulted in an average crop value gain of $56 per acre over that obtained from following a tensiometer irrigation control program at 0.25 atm., although there was no difference in yields. Furthermore, even the low moisture content treatment which gave a decreased sugar yield in comparison with the tensiometer treatment, leaves the penurious farmer $23 ahead of his extravagant neighbor whose sugar yield was higher than his own. If the errors of penny-pinching are overemphasized, the fact that an extravagant program to insure an investment return may lead to still lower net returns is completely forgotten.

Certainly, a plantation must irrigate at very close intervals to assure good yields if it has large areas in soils characterized by low water retention, such as regosols or the eroded, stony or very shallow phases of the N series. Such soils are, however, found characteristically in areas of heavy rainfall which provides much of the water required. Easily 75 per cent of the Hawaiian irrigated cane soils are normal phases of kaolinite and montmorillonite clays which are characterized by higher water retention and which require less frequent irrigation.

If we are to reduce field costs, irrigation costs should be the first to be scrutinized because they are high. If the soil concerned is one which would not lend itself to a more economical irrigation program because of its sandy or gravelly nature, then the soil itself could and should be altered by heavy incorporation of mill waste such as filter cake and bagasse.

2. Using two-thirds of the available soil moisture

Plantations which have active irrigation control programs seem to agree that cane should be irrigated when two-thirds of the available water has been utilized. However, it is difficult to reconcile the different viewpoints within the industry concerning the soil moisture tension level to which this two-thirds moisture depletion point corresponds. For example, cane and soil moisture studies by Clements (2) (3) (4) at Waipio, Oahu, have served as a basis for the selection of 0.25 atmosphere by Waterhouse (16) as the time to replenish the soil moisture. In a recent paper by Clements (4), the relationship between cane growth, soil moisture, and soil moisture tension, was graphically presented. As seen from this graph, the rate of stem elongation during the first and second year showed a sharp decline when two-thirds of the available moisture on his moisture scale had been utilized. However, he gave this point a tension value of only 0.25 atm. The permanent wilting percentage (P.W.P.) for Waipio low humic latosol clay was given as 24.8 per cent water, which he showed as corresponding to 0.80 atm. on the soil moisture tension scale. The moisture content value of 37.4 per cent was shown to correspond to the "O" tension value on the energy scale. Thus, Clements has assigned an energy range of from zero to 0.80 atm. for the whole moisture range of from 37.4 per cent (MFC) to 24.8 per cent water (P.W.P.); hence, from this stems his evaluation of the two-thirds depletion point as being 0.25 atm.

In contrast to the above data, Thorne (14) obtained sorption curves by use of pressure membrane apparatus on this and other Hawaiian soil types, and found a highly significant correlation coefficient between ⅓ atm. and moisture equivalent, 15 atm. and P.W.P. Cornelison at the Experiment Station, HSPA, and Ewart at Kekaha have also independently obtained over 100 curves using standard pressure membrane equipment. A study of these curves shows that 2–4 atm. of soil moisture tension correspond to the two-thirds moisture depletion points. This finding is based on the accepted standard procedure of selecting available moisture as that moisture retained by soil between the 0.33 and 15 atm. percentage.

It appears that Clements (4) has not carefully oriented the soil moisture tension scale to the soil moisture content scale and that there exists a possible basic misconception in the application of the energy concept and its relation to soil moisture content.

3. Desirability of deep-rooting

Sugar cane roots are more abundant in an environment which is warm, well-aerated, and well-supplied with nutrients and moisture. If these conditions predominate in the soil surface, the root system tends to remain shallow. Hence, a growing crop of cane too frequently irrigated will lay down most of its roots at a shallow depth until the longer irrigation intervals during ripening cause root systems to seek water at greater depths. If irrigation intervals are extended drastically at this late stage of the crop cycle, or if drought conditions should prevail at any time, then roots do not get down fast enough to meet the moisture requirements of the heavy above-ground tonnage already established, and severe yellowing and desiccation may result.

A more logical approach is to counteract the tendency of roots to grow at the shallower six-inch depth by forcing them, while the crop is still young, to a greater depth where ample moisture is stored under a program of controlled irrigation intervals. In this way, stalk and foliage growth are balanced and supported by a deeper root system, and the cane mortality rate is very much lower even during the ripening period or during unexpected droughts.

4. Eventual irrigation control

It is widely recognized that there is room for improvement and for more precise controls in the whole field of irrigation. Knowing when to irrigate is not enough; it must also be established how much water to apply at each irrigation round, what are the best preparation methods to reduce run off and increase water retention without waterlogging, and which method of distributing irrigation water in the field is the most economical.

Most plantations cycle their irrigations; i.e., they start a new round immediately after completing the previous one because that is the most convenient thing to do and does not entail taking into consideration aspects which would throw the conveniently automatic cycle off. However, due largely to crop logging, the cycling or automatic approaches to such other field operations as fertilizing, ripening, and especially harvesting, have largely been replaced by the more logical approaches based on individual requirements. This is also true in weed control. There is no reason why the same change cannot be expected in irrigation.

Furthermore, as a study of Figure 1 indicates, present practice keeps the rate

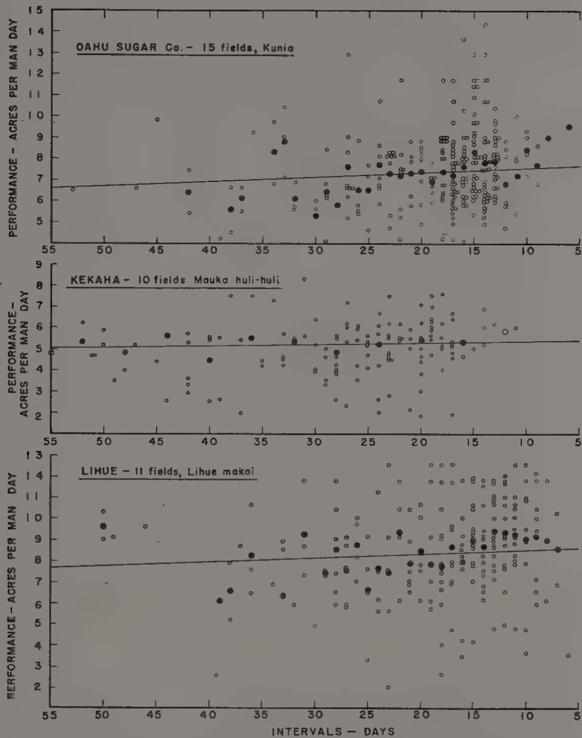

Figure 1. Typical irrigation performance in the 1953 crop following intervals of varying lengths between rounds. Note that the loss in performance is slight whether the intervals between rounds are 10 or 30 days long.

of application relatively uniform regardless of the interval between rounds or the wetness of the soil, as long as water supply is not limiting.

5. Summarization of test data and conclusion

Considering the fact that the tests were administered by different plantations under different cultural and field conditions, the combined coefficient of variability is relatively low. The Experiment Station, HSPA, analyzed the results of the coordinated test as follows:

"(a) *Evidence of Location Effects:* Highly significant for TCA, Y%C, and TSA, thus emphasizing the fact that the treatments were compared over a wide range of different field and other conditions, and hence that the results from the treatments can have quite general application.

"(b) *Evidence of Treatment Effects:* Not significant for TCA or for TSA, but significant for Y%C at P .05. (The significance for TCA and for TSA would not be greater than approximately P .17 and P .20 respectively).

"(c) *Evidence of Interaction between Treatment and Location:* None. This quite definitely indicates that the treatment effects were not influenced by the different effects of the locations, and consequently they apply over all conditions covered by these four tests."

It may, therefore, be concluded that the final phase of the irrigation control program has been satisfactorily completed, and that the use of Bouyoucos blocks is a technique widely adaptable to plantation conditions. While it may also be concluded that irrigating at 5000 ohms in the normal phase of low humic latosol soils is safe for fields of this soil type, a wholesale adoption of technique or index without proper evaluation of local conditions by qualified personnel is not recommended.

A statement made in 1950 (8) bears repeating: "The gypsum block irrigation control system is very flexible and offers promise of plantation-wide irrigation scheduling without imposing stringent control. Both the system and Bouyoucos blocks used are merely tools. In the hands of one who is familiar with the soil-moisture relationship, they can aid materially in reducing irrigation costs and increasing benefits from other agronomic practices by offering better planning and scheduling of fertilization application and weed control, as well as irrigation control."

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Table 1

COMPARISON OF ALL YIELDS UNDER IRRIGATION CONTROL WITH HISTORY OF PAST YIELDS

CROP	NO. OF ROUNDS	INCHES OF RAIN	AGE	TCA	TCA/TSA	TSA	SPAM
Soil type: Intrazonal Dark Mag. Clay (Lualualei) Fld: 13(112.38 acs.) Elev: 20′ M.E: 35–65% Salin: $EC_2 \times 10^5 = 80$							
Field's ave. based on previous crops (1934–1949)............	19	41.30	22.02	86.66	7.89	10.98	.502
Field's Last crop (1949).........	20	63.89	26.55	92.06	7.16	12.85	.484
Field's Record crop (1940)......	18	34.19	19.14	93.89	8.69	10.81	.565
Crop grown under irrig. control (1952)......................	15	62.93	23.33	110.72	7.76	14.27	.612
Soil type: Gray Hydro. Clay (Kaloko) Fld: J(55.66 acs.) Elev: 9–16′ M.E: 46–56% Salin: $EC_2 \times 10^5 = 60$							
Field's ave. based on previous crops (1934–1949)............	18	38.39	22.04	79.30	7.67	10.34	.472
Field's Last crop (1949).........	13	58.16	27.39	95.91	7.31	13.12	.479
Field's Record crop (1934)......	18	33.17	19.08	84.41	8.32	10.15	.532
Crop under irrig. control (1951)..	12	45.61	22.23	92.79	7.78	11.93	.536
Soil type: Gray Hydro. Clay (Kaloko) Fld: 214–2(50.90 acs.) Elev: 6′ M. E:46–56% Salin: $EC_2 \times 10^5 = 250$							
Field's ave. based on previous crops (1935–1950)............	19	43.78	22.32	84.88	8.48	10.17	.457
Field's Last crop (1950).........	18	68.95	23.07	83.45	7.16	11.65	.505
Field's Record crop (1935)......	20		22.06	93.12	7.94	11.72	.532
Crop grown under irrig. control (1952)......................	13	62.53	22.97	91.71	6.76	13.58	.591
Soil type: Low humic Latosol (Lahaina) Fld: G-1(122.29) Elev: 1350′ M.E: 34% Salin: $EC_2 \times 10^5 = 40$							
Field's ave. based on previous crops (1934–1949)............	21	57.86	23.07	70.82	7.97	9.09	.393
Field's Last crop (1949).........	23	82.83	25.13	97.36	8.49	11.47	.456
Field's Record crop (1944)......	16	62.43	23.33	68.11	6.97	11.21	.480
Crop grown under irrig. control (1951)......................	16	70.97	23.15	93.50	8.28	11.29	.488
Soil type: Low humic Latosol (Molokai) Fld: 22(24.92 acs.) Elev: 8′ M.E: 34% Salin: $EC_2 \times 10^5 = 93$							
Field's ave. based on previous crops (1934–1949)............	19	38.40	22.55	89.03	7.81	11.44	.507
Field's Last crop (1949).........	19	57.85	25.25	91.16	6.93	13.15	.521
Field's Record crop (1934)......	18		19.94	91.55	8.60	10.65	.534
Crop grown under irrig. control (1951)......................	16	63.97	23.50	98.46	7.82	12.60	.536
Soil type: Low humic Latosol (Molokai) Fld: 58 & 58F(65.36 acs.) Elev: 800′ M.E: 34% Salin: $EC_2 \times 10^5 = 40$							
Field's ave. based on previous crops (1933–1950)............	21	44.08	21.98	81.93	7.91	10.36	.472
Field's Last crop (1950).........	20	79.88	24.27	90.89	8.61	10.56	.435
Field's Record crop (1935)......	26		22.00	96.31	7.67	12.55	.570
Crop grown under irrig. control (1952)......................	12	73.09	23.07	95.93	7.75	12.38	.537
Soil type: Low humic Latosol (Molokai) Fld: G-3 & G-3F Elev: 1100′ M.E: 34% Salin: $EC_2 \times 10^5 = 40$							
Field's ave. based on previous crops (1935–1950)............	21	54.33	22.24	78.70	7.85	10.11	.452
Field's Last crop (1950).........	17	79.56	24.05	88.64	7.90	11.22	.467
Field's Record crop (1935)......	23		22.98	93.13	7.31	12.73	.554
Crop grown under irrig. control (1952)......................	12	72.58	23.95	98.12	6.91	14.23	.595

1. SPAM = Sugar Per Acre Month
2. Salinity Rating: $EC_2 \times 10^5$ = 75 Low
   " = 75–150 Medium
   " = 150–275 High
   over 275 Very High

EC_2 = 1:2 Soil/Water extract

Table 2

RECOMBINATION OF PLOTS BASED ON AVERAGE ACTUAL READINGS AT TIME OF IRRIGATION

Kekaha Test—83 I

Plots	Actual Av. of Readings at time of Irrig.	t .20 atm. Group		t .30 Ten. Group		2000 R Group		5000 R Group		15,000 R Group		50,000 R Group	
		YIELD OF PLOTS											
		TCA	TSA	TCA	TSA	TCA	TSA	TCA	TSA	TCA	TSA	TCA	TSA
1	.25 atm.	104.8	17.2										
2	17,900 R									118.5	17.7		
3	1,800 R					105.9	17.4						
4	16,650 R									110.6	17.3		
5	2,260 R					111.2	17.1						
6	.31 atm.			107.3	17.9								
7	3,135 R					119.4	17.3						
8	4,830 R							130.8	19.0				
9	.26 atm.	109.2	16.8										
10	2,280 R					101.2	15.6						
11	.21 atm.	98.3	16.7										
12	1,166 R					100.1	16.4						
13	63,400 R											83.0	13.8
14	4,220 R							103.2	17.2				
15	6,660 R							105.5	17.0				
16	.15 atm.	106.7	16.7										
17	32,920 R											95.2	14.9
18	6,220 R							105.2	16.2				
19	.29 atm.			106.1	16.3								
20	2,480 R					91.3	14.2						
21	3,730 R							107.1	17.3				
22	.31 atm.			102.2	15.7								
23	13,180 R									82.0	13.1[1]		
24	32,700 R											98.0	16.9
25	47,000 R											103.4	15.4
26	44,000 R											105.4	17.6
27	3,240 R					115.1	18.6						
AVERAGE YIELDS		104.8	16.9	105.2	16.6	106.3	16.7	110.4	17.3	103.7	16.0	97.0	15.7

1. Plot is poorest (rocky & steep) of all in experiment. Poor stand of cane due more to this and to frequent breaks n line during irrigation than to irrigation treatment.

Table 3

GENERAL DATA COVERING TEST AT EACH LOCATION

	Kekaha	Lihue	Oahu	Average
CROP				
Cane Variety	37–1933	37–1933	37–1933	37–1933
Started	7/4/51	6/13/51	12/11/50	
Harvested	5/6/53	6/2/53	10/30/52	
Age (Months)	22.0	23.7	22.6	22.8
Treatment Period (months)	19.0	19.7	19.6	19.4
SOIL				
Field	38	24L		
Elevation	260′	260′	180′	233′
Soil Type	Low Humic Latosol Clay			
Family	Molokai (N1)	Kahana (N4)	Molokai (N1)	
Surface Soil Depth	12″	10–12″	(Not Differentiated)	12″
Color	Red	Dk. brn. red	Red	Red
Subsoil Color	Red Brown	Lt. Red brn.		Red brn.
Mass Root Zone Depth	12″	12″	12″	12″
WEATHER				
Temp. during crop cycle	Above normal (>10 Grth.°)	Above normal (>20 Grth.°)	Above normal (>45 Grth.°)	
Rainfall during crop cycle	37.2″	79.4″	56.1″	57.6″
Normal for same period	57.0″	103.8″	60.0″	73.6″
Number substantial rains (>2.5″) during test	5	5	5	5
LAYOUT & HARVESTING				
Total acreage in test	12.7	13.9	14.9	13.9
No. of replicates @ X, L B Treatment	7	7	7	7
No. of replicates W (observation) treatment	5	3	3	4
Harvesting Method	Hand cutting	Hand cutting	Hand cutting	
Juice sampling	Cuban A	Mill crusher	Mill crusher	
FERTILIZATION				
N (lbs.)	274	186	243	234
P205 (lbs.)	80	206	210	165
K20 (lbs)	250	183	285	239
IRRIGATION				
Av. Appl. Per Rd. Ac. Inch	5	5	5	5
Av. Eval. One Million Gal. Water $	10.00	10.00	10.00	10.00
Av. Cost Per Hour Labor $	1.645	1.645	1.645	1.645

Table 4

GENERAL DATA COVERING EACH TREATMENT AT EACH LOCATION

		Kekaha				Lihue				Oahu				Average			
	Units	X	T	B	(W)	X	T	B	(W)	X	T	B	(W)	X	T	B	(W)
IRRIGATION																	
Total Rounds During Crop Cycle..		28	46	25	21	31	53	24	16	(23) 34	39	21	17	31 (27)	46	23	18
Rounds applied before treatment started......................		6	6	6	6	8	8	8	8	7	7	7	7	7	7	7	7
Rounds called for by treatments...		22	40	19	15	23	45	16	8	(16) 27	32	14	10	24 (20)	39	16	11
Av. Interval between treatment rds.	Days	22	12	26	33	24	12	33	69	(31) 17	15	35	38	21 (26)	13	31	47
Field Irrig. Performance for Intervals given x7..................		5.33	5.40	5.26	5.20	8.30	8.50	8.15	7.65	7.15	7.45	7.10	7.0	6.93	7.12	6.84	6.62
YIELDS																	
Sugar Per Acre..................	Tons	16.8	16.7	16.8	15.7	13.8	13.8	13.8	12.9	15.7	16.5	15.9	16.1	15.4	15.7	15.5	14.9
Sugar Per Acre Per Month.......	Tons	0.764	0.759	0.764	0.714	0.582	0.582	0.582	0.544	0.695	0.730	0.704	0.712	0.680	0.690	0.683	0.629
Cane Per Acre..................	Tons	105.5	105.0	108.6	97.0	105.3	108.9	107.1	106.0	115.4	120.6	120.0	120.5	108.7	111.5	111.9	101.5
Quality Ratio..................		6.3	6.3	6.5	6.2	7.6	7.9	7.7	8.2	7.4	7.3	7.5	7.5	7.1	7.2	7.2	7.2
STATISTICAL ANALYSIS OF VARIANCE..................	For.	D.F.	T.C.A.	Y%C	T.S.A.	D.F.	T.C.A.	Y%C	T.S.A.	D.F.	T.C.A.	Y%C	T.S.A.	D.F.	T.C.A.	Y%C	T.S.A.
Source—Locations (L)...........														2	1043.5	46.6	52.73
Blocks..................		6	181.12	.67	2.64	7	85.12	.48	1.26	6	69.22	1.22	.54	19	110.4	.77	1.47
Treatments (T)..........		2	14.78	.73	.10	2	26.65	.37	.02	2	57.18	.33	1.37	2	46.9	1.33	.43
T X L..................														4	25.9	.04	.53
Error..................		12	69.21	.33	1.20	14	61.57	.36	1.08	12	154.15	.36	2.60	38	93.2	.34	1.53
Total..................		20				23				20				65			
General Average................			106.0	15.8	16.7		107.1	12.9	13.8		118.6	13.5	16.0		110.4	14.0	15.4
Coef. of Var....................			7.8%	3.6%	6.6%		7.3%	4.7%	7.5%		10.5%	4.4%	10.1%		8.8%	4.1%	8.0%

Table 5

IRRIGATION LABOR AND WATER COST COMPARISON OF 4 SYSTEMS OF IRRIGATION CONTROL AT 3 PLANTATIONS

	KEKAHA				LIHUE				OAHU				AVERAGES			
	Field[1] Prac-tice	Tens. 0.25 atm.	Blocks 5000 ohms.	Blocks[2] 50,000 ohms.	Time Inter-val	Tens. 0.25 atms.	Blocks 5000 ohms.	Blocks[2] 50,000 ohms.	Moist. Sam-pling	Tens. 0.25 atm.	Blocks 5000 ohms.	Blocks[2] 50,000 ohms.	Field Prac-tice	Tens. 0.25 atm.	Blocks 5000 ohms.	Blocks[2] 50,000 ohms.
$ Cost per round per acre																
Irrig. labor – $1.645/hr.	$2.47	2.44	2.50	2.53	1.59	1.55	1.61	1.72	1.78	1.77	1.85	1.88	1.94	1.92	1.99	2.06
Irrig. water – $10/mill. gal.	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Total	3.83	3.80	3.86	3.89	2.95	2.91	2.97	3.08	3.29	3.13	3.21	3.24	3.29	3.28	3.35	3.42
$ Cost per ton sugar																
Irrigation labor	$4.16	6.72	3.72	3.38	3.57	5.95	2.80	2.13	3.85	4.18	2.44	1.99	3.86	5.62	2.99	2.66
Irrigation water	2.27	3.75	2.02	1.82	3.06	5.22	2.37	1.69	2.95	3.21	1.80	1.44	2.76	4.06	2.06	1.65
Total	6.43	10.47	5.74	5.20	6.63	11.17	5.17	3.82	6.80	7.39	4.24	3.43	6.62	9.68	5.05	4.31
$ Cost per crop per acre																
Irrigation labor	$69.2	112.2	62.5	53.1	49.3	82.1	38.6	27.5	60.5	69.0	38.9	32.0	59.7	87.8	46.7	37.5
Irrigation water	38.0	62.6	34.0	28.6	42.2	72.1	32.7	21.8	46.2	53.1	28.5	23.1	42.2	62.6	31.7	24.5
Total	107.2	174.8	96.5	81.7	91.5	154.2	71.3	49.3	106.7	122.1	67.4	55.1	101.8	150.4	78.4	62.0
$ Cost + or –	Base	+68	–11	–26	Base	+63	–20	–43	Base	+15	–39	–52	Base	+49	–23	–40
Cash Value of Crop/Acre Estimated at $124/ton																
Before irrig. cost deducted	$1428	1420	1428	1335	1173	1173	1173	1097	1335	1403	1352	1369	1312	1332	1318	1267
After " " "	1321	1245	1332	1253	1082	1019	1102	1048	1228	1281	1285	1314	1210	1182	1240	1205
Gain or loss per acre	Base	–76	+11	–68	Base	–63	+20	–34	Base	+53	+57	+86	Base	–28	+30	– 5

1. 2000 ohms is actually not present field practice at Kekaha, but was used in order to obtain information at this level. Plantation practice is represented by blocks at 5000 ohms. The 50,000 ohm treatment, installed in mauka areas, represents actual field practice there because limited water supply often results in irrigations at readings even higher.

2. This treatment for all three plantations was for observation only. The results were obtained from three to five replications, instead of seven, so that the data are not of Grade A quality.

IRRIGATION CONTROL WITH TENSIOMETERS AND IRROMETERS

A. D. WATERHOUSE AND H. F. CLEMENTS[1]

Hawaiian Commercial and Sugar Company, Ltd. uses tensiometers to guide the control of irrigation on 25,000 acres of sugar cane. Tensiometers are placed near the point where irrigation is started for each field. If the soil in the field is uniform, only one instrument is used. Where there is a variation of soil within a field, additional instruments are installed. Daily readings are plotted on a graph. The slope of the moisture extraction curve is projected to the 0.25 atm. mark. By counting back from this point to the date of the last irrigation, the desired irrigation interval is determined. These data are used to schedule the distribution of water throughout the plantation and the time to irrigate each individual field. Sandy soils on the plantation require irrigation about every eight days throughout the year. During the winter months, when growth is slow, the heavier-textured soils are irrigated about every 20 days, while in summer, irrigations every 10 days are needed. Moisture-tension curves are established for the various areas and soil types on the plantation. The tensiometer works especially well since the soils have moisture-tension curves which indicate that most of the available water is released at relatively low tensions. The range in tension for the various soils, when 50 per cent of the available water has been extracted within the 12- to 24-inch zone, is from 0.08 to 0.33 atm.

Research in irrigation to explore the relationship between soil moisture tension and productivity has been a major project of the plantation since the early part of 1947, when tensiometers were first installed in the fields of the former Maui Agricultural Company for guides to proper timing of irrigation intervals. Interest in the use of the tensiometer for determining the point in soil moisture tension at which irrigations should be applied to produce maximum yields had been aroused by the work of Clements (4), started in October 1946, at the Waipio Substation of the Experiment Station, HSPA. The tensiometer reading of 25 used at H C & S as the time to irrigate was based on the Waipio studies.

The first replicated irrigation experiment where irrigation was effected at tensiometer readings of 25, 40, 55 and 70, was installed in August 1948. Since then, 13 additional field tests have been installed. Five of these are classified as observation tests; the remaining eight are well-replicated field experiments. The design and treatments imposed on the 13 tests vary considerably from the first one installed in 1948.

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Table I. Pertinent Facts and Data Related to Field Experiments Harvested in 1953

Field No.	Soil	Cane	Tensiometer Control		Age Harvest	Rainfall Amt.	Total Plots	LSD (TSA)			Treatments—Atmospheres Tension						
		Variety	Start	Finish	Date	Date	Reps.	1%	5%	Yield	.15	.15 then +.12/mo.	.25	.45	.65	.25–.45	.25–.65
809	Kawaihapai family (alluvial soil)	44–3098	May 6 1951 After 4 Irrig. Rnds.	Oct. 1 1952	25 mo. Feb. 18 1953	6.34″ Feb. 22 1952	25 5	1.02	0.74	TCA TSA Y%C Irrig. Rnds.	. . . .	. . . .	87.96 12.21 13.90 35.6	82.10 11.42 13.91 27.2	75.19 10.26 13.66 22.6	82.51 11.51 14.04 31.8	79.89 11.11 13.91 29.8
715	Honouliuli family (grey hydromorphic soil)	37–1933	Aug. 30 1951 After 9 Irrig. Rnds.	Jan. 15 1953	25 mo. June 8 1953	4.68″ Jan. 20 1952	30 6	ns	ns	TCA TSA Y%C Irrig. Rnds.	. . . .	. . . .	108.40 15.74 14.50 43.0	105.40 15.64 14.80 37.0	96.60 14.25 14.80 26.0	100.80 15.05 14.90 40.0	102.20 15.36 15.30 36.0
605	Molokai family (low humic latosol)	37–1933	Apr. 9 1952 14 Irrig. Rnds.	Apr. 9 1953	23.5 mo. Aug. 8 1953	4.40″ Jan. 20 1952	14 2	None Calcu	lated	TCA TSA Y%C Irrig. Rnds.	105.80 15.20 14.40 47.0	111.80 14.10 12.60 34.0	98.80 14.50 14.70 37.0	102.10 13.40 13.10 30.0	96.70 12.60 13.00 29.0	96.00 12.90 13.50 35.0	99.50 13.30 13.40 33.0

Yield data from irrigation experiments harvested in the 1953 crop at H C & S have shown significant results. From this information, together with data from the observation tests that were also harvested, experiments have been designed and installed from which, when yield information from both the plant and ratoon crops is acquired, will be determined the point of soil moisture-tension where irrigations should be applied to produce maximum yields.

FIELD EXPERIMENTS IN 1953 CROP

Three experiments were harvested from Fields 809, 715 and 605 during 1953. The pertinent facts and harvest yields related to these experiments are given in Table 1.

The experiments included treatments in which the limiting moisture-tension values varied with time, as well as treatments with constant limiting moisture-tension values. In Field 605, some plots were irrigated the first year at 0.15 atm. and during the second year, these same plots were irrigated at increasing tension increments of 0.12 atm. per month until a maximum tension of 0.63 was reached. All three experiments had split treatments in which the 0.25–0.45 split-treated plots received irrigations at 0.25 atm. the first year and 0.45 atm. the second year, whereas the 0.25–0.65 plots received irrigations at 0.25 atm. the first year and 0.65 atm. the second year. The second-year treatment in all of the plots of these experiments ceased when ripening was imposed.

The reason for the installation of these split treatments was to see if the cane plant, when in a more mature state of growth, would be able to extract soil moisture as readily at higher moisture stresses, and/or if such treatment would be reflected in higher sugar yields. The area of each treated plot was greater than one acre.

Tensiometers were placed in the center of each plot at a depth of approximately 20 inches. They were installed after the second irrigation round was applied, after which additional rounds were applied so that they were firmly established in the soil and in good working order before treatments were started.

In Field 809, a plaster of Paris block and a nylon unit were installed in each plot at the same depth as the tensiometer cup. Each unit was read and recorded daily to establish relationship between these soil moisture measuring devices.

In comparing the readings of the tensiometers, nylon and plaster of Paris blocks during the first few months of treatment, there appeared to be a close relationship between the tensiometers and the nylon blocks. There was no suggestion at all of a relationship with the readings of the plaster of Paris blocks, the reason for this being that the treatments in this experiment called for irrigations at tensions lower than one atm. Failing to find any relationship at all, the daily readings on the plaster of Paris blocks were discontinued on the first of November 1951. After the crop had progressed and the soil had been subjected to further drying cycles, the relationship that had been found earlier between the tensiometers and nylon blocks disappeared entirely.

In Field 809, soil samples from the first and second foot of depth were collected separately from each of the five blocks of treatments in the experiment, thus making a total of 10 samples. Moisture-retention curves were determined on these soils and the moisture tension value at various percentages of available moisture are given in the table below. For the available water calculation, the

tension value corresponding to the upper limit of available water was considered 0.04 atm.

Depth of Sample	% Moisture Used	Tension in Atm. (Blocks) I	II	III	IV	V
1st foot	80	0.55	0.40	0.71	1.00	1.37
2nd foot	80	1.00	0.86	1.13	1.10	1.75
1st foot	70	0.27	0.24	0.31	0.36	0.61
2nd foot	70	0.37	0.33	0.40	0.52	0.79
1st foot	60	0.18	0.17	0.18	0.19	0.35
2nd foot	60	0.19	0.21	0.24	0.25	0.40
1st foot	50	0.13	0.13	0.12	0.12	0.24
2nd foot	50	0.13	0.16	0.15	0.13	0.24

Figure 1 shows a comparison of the percentage of available water extracted prior to irrigation with relative yields in both cane and sugar. Seventy-five per cent of the available water was extracted when plots were irrigated at 0.65 atm., 69 per cent at 0.45 atm., and 60 per cent at 0.25 atm. An upward projection of these curves would probably level out between 50 and 60 per cent. This again indicates that higher yields could be expected when irrigations are applied at lower tensions, or when a lower percentage of available water is used up.

As further substantiation of the above statement, studies on the mainland with other crops have come to the same conclusion. Baver (2) makes the following statement: "I have analyzed the results from a large number of other crops and it seems like the maximum vegetative growth at least, is obtained when the soil is irrigated when about 50 to 60 per cent of the available water has been used."

To quote from the monograph "Soil Water and Plant Growth" by L. A. Richards and C. H. Wadleigh (7): "Reduced rates of fruit growth were thus observed when the average moisture content of the upper three feet of soil was reduced below about 50 per cent of the available capacity." This statement refers to studies made in 1940 by Aldrich, Lewis and Work (1) on the response to irrigation of Anjou pear trees on Meyer clay adobe soil in Oregon where the W-1 plots that gave the highest yields were frequently irrigated throughout the season; that is, irrigated when about 50 per cent of available water was removed in the first three feet of soil. . . . "Tests by other workers indicate that moisture depletion

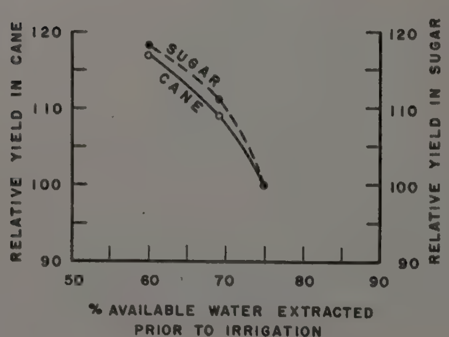

Figure 1. Relative yields in cane and sugar vs. per cent of available water extracted prior to irrigation.

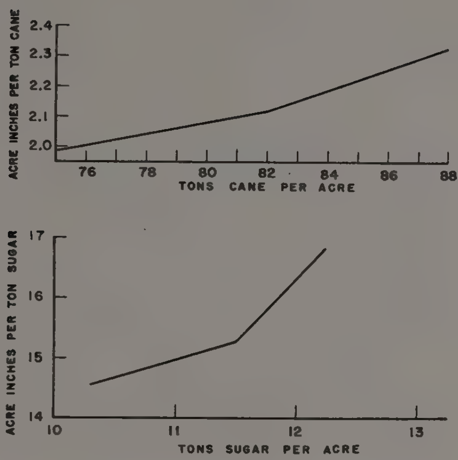

Figure 2. Acre inches per ton cane vs. tons cane per acre, and acre inches per ton sugar vs. tons sugar per acre.

by as much as 50 per cent of the available range may cause a significant depression in the yields of potatoes."

In 1950, Blair, Richards and Campbell (3) reported on measurements of the rate of elongation of sunflower plants in relation to moisture depletion as follows: "These data show there is a definite falling off in the growth rate before half of the available water is used and that growth ceased some time before the permanent-wilting percentage was reached."

Figure 2, using the data from the plots in Field 809 that were irrigated at 0.25, 0.45, and 0.65 atm. throughout the crop, shows a comparison of the ratio of irrigation to cane production versus cane yield and the ratio of irrigation to sugar production versus sugar yield, and indicates that in order to increase yields, amounts of water must be increased. It also shows that the ratio of the amount of water to yield does not follow a straight line relation with yield per acre. The salient data of the experiment may be tabulated as follows:

Treatment	TCA	TSA	Lbs. Water per lb. cane	Lbs. Water per lb. sugar
0.25 atm.	87.96	12.21	264	1900
0.45 atm.	82.10	11.42	240	1724
0.65 atm.	75.19	10.26	226	1654

Presented graphically in Figure 3 are the comparisons of sugar yields versus number of irrigation rounds in a crop, and tons sugar per round versus number of irrigation rounds in a crop.

A correlation was run comparing both cane and sugar yields with the total number of irrigation rounds each treatment received. As shown in Figures 4 and 5, both comparisons showed high significance to the one per cent level. It might be pointed out that the cane grown under field practice conditions yielded 100.46 tons cane per acre, 7.59 tons cane per ton sugar, and 13.24 tons of sugar per acre, as compared with a yield of 87.96 tons cane per acre, 7.20 tons cane per ton of sugar, and 12.21 tons of sugar per acre for the plots that were irrigated at 0.25 atm. The cane under normal field practice received 52 irrigation rounds as against an average of about 36 rounds for the 0.25 atm. plots. This would indicate that

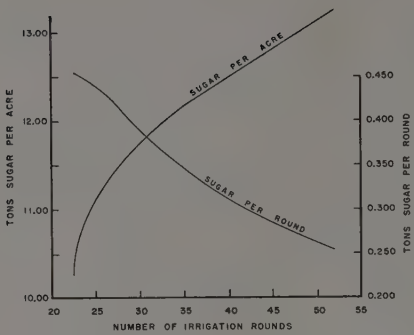

Figure 3. Tons sugar per acre and tons sugar per irrigation round vs. number of irrigation rounds.

the 16 additional rounds produced 12.50 more tons of cane and 1.03 more tons of sugar.

From the results of this experiment in Field 809, it appears that: first, to obtain maximum production, cane must be irrigated at soil moisture tensions no higher than 0.25 atm.; and second, by irrigating at higher tensions during the second season of growth, no increases in either cane or sugar yields can be realized.

Crop log samples were also collected from each plot in Field 809 at 35-day intervals starting on June 28, 1951, when the plants were five months old, and ending on September 24, 1952, with the termination of the irrigation treatment and the inauguration of the ripening schedule. This period covers 15 months of active crop growth under irrigation treatment. The authors wish to express their indebtedness to Minoru Isobe, Agricultural Chemist at H C & S, for the section of discussion on the evaluation of crop log data.

The mean value of the green weight of sheaths, leaf nitrogen, and sheath moisture derived from the 15-month period, produced interesting information about the response of the plant to the irrigation regime.

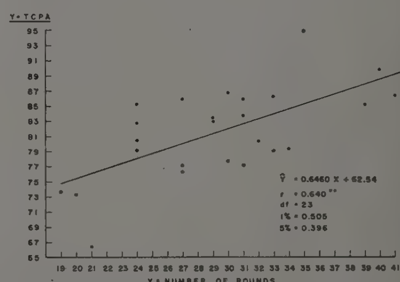

Figure 4. Number of irrigation rounds vs. tons cane per acre.

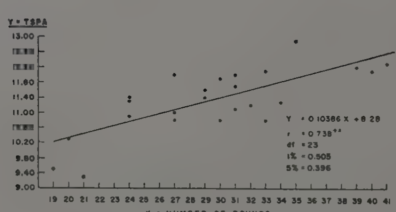

Figure 5. Number of irrigation rounds vs. tons sugar per acre.

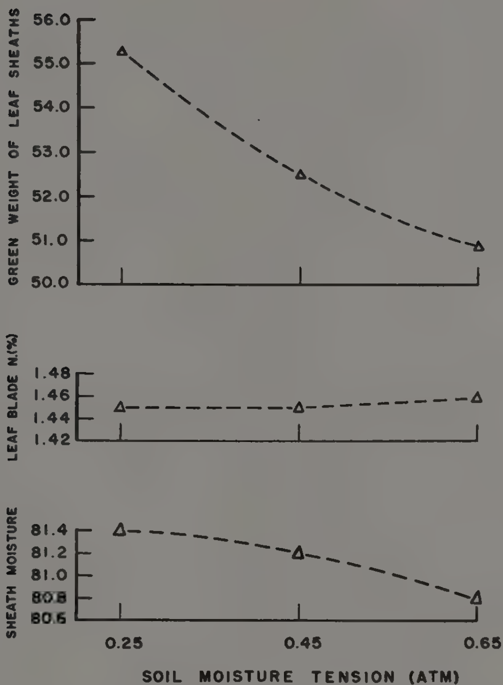

Figure 6. The top graph presents the growth index vs. soil moisture tension; the middle graph, the leaf nitrogen vs. soil moisture tension; and the bottom graph, the sheath moisture vs. soil moisture tension.

In the discussion to follow, only the 0.25, 0.45 and 0.65 atm. treatments will be compared.

The mean green weight is highest with the 0.25 atm. treatment as indicated in the top graph in Figure 6. The gains over the 0.45 and 0.65 atm. treatments are statistically significant at the five per cent and one per cent probability levels, respectively.

Clements, et al (5), have determined the partial regression of various factors on growth rate, and have found significance with the green weight of sheaths, rate of leaf emergence, maximum and minimum temperatures, sheath moisture, age, total sugars and soil moisture. Of these, the green weight was the dominant factor.

A correlation coefficient of 0.68 which was significant at the one per cent level, was found between the green weight of sheaths and tons cane per acre. A higher value could be expected if the other factors (besides green weight) were accounted for in the correlation. The green weight, itself, is a good indication of the rate of growth (growth index) of a crop.

No difference in the mean leaf nitrogen was found between treatments. (Figure 6, center) As leaf nitrogen is related to sheath moisture (5, 6), it is well to examine the data on sheath moisture.

There is a trend toward higher mean sheath moisture with lower soil moisture tension as indicated in the bottom graph in Figure 6. There is no significant difference between 0.25 and 0.45 atm. treatments although there is real difference between the former and 0.65 atm.

Although soil moisture was more easily available in the 0.25 than in the 0.45 atm. plots, the plants did not respond with a higher sheath moisture. Yet, that the plants did utilize more soil moisture is indicated by the differences in cane tonnage.

The fact that no difference in leaf nitrogen was found may indicate that soil nitrogen was a limiting factor in this test and was responsible for no increase in sheath moisture with greater soil moisture availability. Possibly with the application of higher amounts of nitrogen, more cane tonnage could have been realized from the 0.25 atm. plots.

Clements, et al (5), have found eight factors affecting sheath moisture. Of these, leaf nitrogen was the dominant factor. The positive correlation between sheath moisture and leaf nitrogen is well known among investigators familiar with the crop log (5, 6). Further research is required to study the effect of the relationship between soil moisture availability, sheath moisture, and nitrogen, on cane tonnage.

Difficulty was experienced in maintaining control of irrigations in the various treatments in Field 715 because the plots were located in a gray hydromorphic soil which cracks severely on drying. Because of this, especially during the early stage of the crop, constant maintenance was necessary to keep the tensiometers in working order. After treatments were imposed, and constant plot-by-plot inspections were made to locate soil variation within and between plots, individual soil samples were taken from each plot and moisture-retention curves were run in the laboratory. It was found that there was considerable variation in the moisture-holding characteristics from one plot to the next. It was then suspected that variation might very likely occur within each plot.

Although no significance can be attached to the yield differences found in the Field 715 experiment, there is a trend favoring irrigations at 0.25 atm. It is very likely that, due to the soil variation that existed within the experimental area, no significant differences were found. Also, the difficulty experienced in maintaining good control during the early part of the crop could be a contributing factor.

Treatments were started on April 9, 1952, in Field 605 when the crop was about seven months old and after 14 rounds of irrigation had been applied. About two months after treatments were imposed, it was found that serious dry spots were developing in five out of the total seven blocks of treatments. These were especially noticeable in the plots that called for irrigations at higher tensions. Because of this unforeseen variable which would affect the final results, it was decided to discard the five questionable blocks and continue treatment on two replicates.

As there are only two replications of each treatment, no significance can be attached to the differences. These comparisons show the same trend favoring irrigations at low soil moisture tensions. However, when these yield results are combined with comparable data from Fields 809 and 715, the following analysis of variance is obtained:

Treatment	TCA	TC/TS	TSA	Irr. Rounds
Irr. at 0.25 atm. throughout crop	99.08	6.98	14.20	39
Irr. at 0.45 atm. throughout crop	95.95	7.01	13.68	32
Irr. at 0.65 atm. throughout crop	88.40	7.10	12.45	25
Irr. at 0.25 atm. 1st yr., then at 0.45 atm.	93.02	6.95	13.38	36
Irr. at 0.25 atm. 1st yr., then at 0.65 atm.	93.22	6.95	13.41	33
LSD at 5% level	4.50		0.71	
LSD at 1% level	5.98		0.95	
Coefficient of variation	6.11%		6.79%	

These experiments were rake harvested and transported to the Puunene Mill by Tournahaulers. Plot yields were determined by weighing not only all of the cane, but all of the juice from each plot, as well as by running crusher juice samples and Cuban A mill samples for determining field trash. Each of these plots was treated as each individual field would normally be treated, so that accurate plot yields for cane and sugar were obtained.

LABORATORY STUDIES FROM FIELD 809 SOIL

Studies on soils from a replication of the experiment in Field 809 were made in the greenhouse laboratory. The soils were placed in five-gallon cans in which tensiometers, plaster of Paris and nylon blocks were installed and in which sunflowers were planted as the indicator plants. (Figure 7) After the sunflowers were established, the soils were brought to maximum field capacity; then, without any further irrigation, readings of the three measuring devices and weights of the cans were taken daily until the soil moisture indicated near-permanent wilt. This procedure was repeated through several drying cycles and, on the final run, the soil

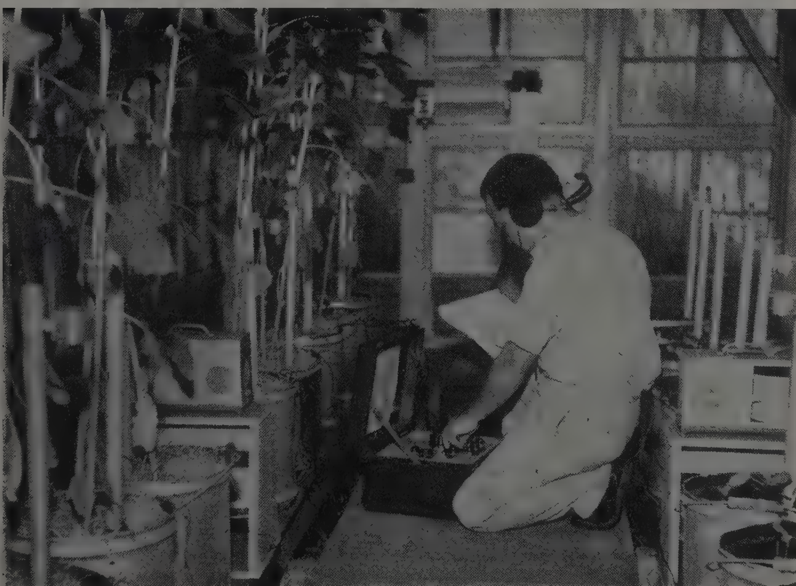

Figure 7. Tensiometers are compared with nylon and plaster of Paris blocks in the greenhouse.

Figure 8. A trench was dug to show the depth of roots of variety 37–1933 which was irrigated at 0.25 atm. Note the roots in the bank at the right which are nearly 30 inches below the surface. Under similar circumstances, roots may be found six feet below the surface.

was allowed to dry to the actual permanent wilt as shown on the indicator plants. The objects of this study were to find relationships between the three measuring devices and the actual soil moisture percentages determined by the daily weighing of the cans, and to find relationships between these findings and the moisture-retention curve determined by the use of porous and pressure plate apparatus.

The results showed a close relationship between the tensiometers, the moisture-retention curve, and actual soil moisture up to about 0.80 atm., which is near the top limit of the instrument. The plaster of Paris blocks showed fairly close agreement on the upper range of the curve above one atm., and no response at all at soil moisture tensions below one atm. The nylon blocks, which looked very promising at first, later appeared to be quite unreliable. Although they showed a definite curve pattern on each drying cycle, they would not follow the same line so that no significance could be attached to any given resistance reading.

OBSERVATION TESTS

Within an experimental area in Field 809, one level ditch was divided into six special plots for an observation test. The following treatments of two replicates were imposed:

1. Irrigation at 0.15 atm. tension
2. Irrigation at 0.25 atm. tension
3. Irrigation at 2.00 atm. tension

Tensiometers which were placed at a depth of about 20 inches were used to determine the time to irrigate in treatments No. 1 and No. 2. For treatment No. 3, irrigations were determined by nylon blocks because the tension of 2.00 atm. is beyond the degree of dryness that tensiometers can indicate.

The purpose of this observation test was to attempt to demonstrate symptoms of over-irrigation on the plots that were irrigated at 0.15 atm., and symptoms of under-irrigation on the plots irrigated at 2.00 atm., in comparison with the 0.25 atm. plots which, at that time, closely approximated plantation practice.

Special attention was give to making frequent and careful observations of these plots. The first outstanding observation was the complete lack of plant moisture stress in the plots which were being irrigated at 0.15 atm. In fact, these plots were showing faster growth than plantation practice plots. On the other hand, the plants in the 2.00 atm. plots were showing real signs of moisture stress. Bi-weekly growth measurements were taken, and for the first eight-week period, from July 5 to August 30, the following was recorded:

Plots irrigated at 0.15 atm. had grown 41.2 inches
Plots irrigated at 0.25 atm. had grown 33.6 inches
Plots irrigated at 2.00 atm. had grown 0.0 inches

These plots went on treatment on May 6, 1951. In the 2.00 atm. plots, from May to July, the soil moisture climbed to about 1.22 atm. and leveled off. The cane in these plots showed such severe symptoms of drought that the cane would die if the plots were not irrigated. Before irrigations were ordered, the root system was examined. A very unhealthy system of roots was found extending downward only about 16 inches. In the 0.15 and 0.25 plots, a very healthy root system was found extending down beyond the two-foot level. (Figure 8) From the observations made in the 2.00 atm. plots, it may be surmised that there is small movement of soil water when there are no plant roots to take it up. This statement is substantiated by moisture determinations taken at this time which indicated that in the soil horizon where the roots were, the soil moisture tensions were at 15 atm., indicating permanent wilt, while below the 16-inch level, where there were no roots, the tension was 1.22 atm. Three rounds of irrigation given to these 2.00 atm. plots caused renewed growth of 21.0 inches and sent the roots down to the two-foot level. Measurements prior to the first round showed no growth at all. When these plots were returned to treatment, they again showed signs of moisture stress. Because of this second setback, and because of the indication that further treatment would cause considerable loss of sugar, these plots were put back on the plantation practice schedule on May 6, 1952.

Figure 9 shows both the comparison of rate of growth for the 0.15 and 0.25 atm. plots and the accumulated growth of the same two treatments. The 0.15 atm. plots had 3.48 feet more growth than the 0.25 atm. plots.

Another observation, which was made during the progress of this test and which merits serious consideration in designing irrigation experiments, is the border effect. It was found in this test that the irrigations applied on one plot would influence growth five lines in from the border, or approximately 25 feet. This could very well account for the disappointing results in the tensiometer experiment in Field 308, where the plots ranged in size from 0.20 to 0.51 of an acre and contained approximately 18 lines of variable length. Border effect could easily cover as much as 50 per cent of the total area in these small plots.

There were three observation tests harvested in the 1953 crop. Outside of the one in Field 809 described above, another was in Field 715 adjacent to the tensiometer experiment, and the third was in Field 602, a low humic latosol of the

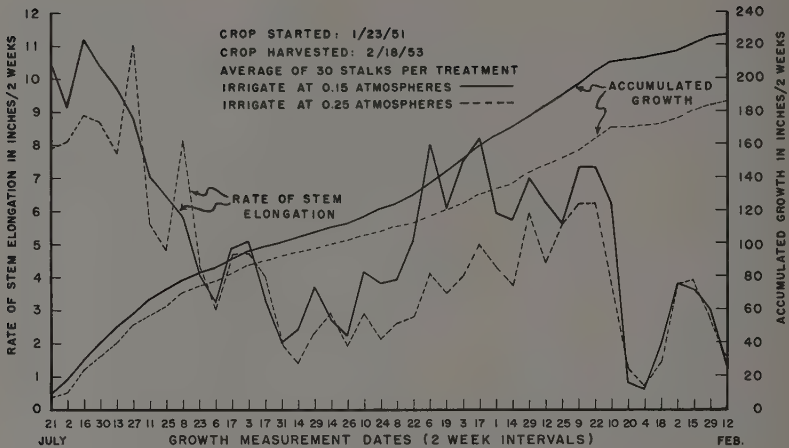

Figure 9. Rate of growth and accumulated growth of the 0.15 and 0.25 atm. plots.

Molokai family in the normal phase. Treatments imposed were the same in each: irrigations at 0.15, 0.25, and 2.00 atm. As in Field 809, tensiometers placed at the approximate depth of 20 inches were used to determine irrigations in the 0.15 and 0.25 atm. plots. Nylon blocks placed at the same depth were used in the 2.00 atm. plots. Due to the difficulty experienced in securing accurate readings from the nylon blocks, as first found in Field 809, and because of the drastic treatment given to the 2.00 atm. plots, these plots had to be withdrawn and put back on normal practice as the lack of sufficient irrigations caused distressed conditions.

The following is a summary of the yield data and irrigation rounds applied to the two plots of the 0.15 and 0.25 atm. treatments in each of the three observation tests, together with the two plots of each from the experiment in Field 605, a total of eight comparisons:

Treatment	TCA	TC/TS	TSA	Irr. Rounds
Irr. at 0.15 atm. throughout crop	115.59	7.63	15.14	68
Irr. at 0.25 atm. throughout crop	101.34	7.39	13.71	36
LSD at 5% level	11.02		ns	
LSD at 1% level	16.30		ns	
Coefficient of variation	8.59%		8.56%	

In studying the above yield data, it must be remembered that with the exception of the plot yields from Field 605, where the plots were large enough so that juice weights were obtained and accurate sugar and cane yields were determined, these yields are from small plots that range from 0.25 to 0.60 acre. No guard lines were taken out to eliminate the border effect which was noticeable during the growing period. The net cane yields were based on the average per cent trash deduction that was used for the field and the sugar was calculated from the Quality Ratio of Cuban A mill juice samples.

Although these yields may be called only an indication where the analysis of variance showed no significant difference in sugar yields and only a significant

gain to the five per cent level in cane yields favoring the 0.15 atm. treatment, it appears that the trend is strongly in favor of irrigations at very low soil moisture tensions.

EXPERIMENTS INSTALLED FOR 1955 CROP

From knowledge acquired in conducting the experiments and the observation tests harvested this year, and from the analysis of yield data, have come refinements in the designs and techniques which were used in the installation of six new experiments for the 1955 crop.

These experiments are all located in plant fields, each representing one of the six major soil types on the plantation. In each experiment, four irrigation treatments are each replicated six times. The plots are of level ditch size.

Extensive testing led to the decision to use irrometers in place of tensiometers. The new instrument is not only better constructed, but needs minimum maintenance. Irrometers, after being thoroughly checked, were placed at a depth of 18 inches in the experimental plots and will be used to determine irrigation intervals at 0.15, 0.25, 0.35, and 0.45 atm., until the ripening period begins.

All six experiments will be carried through the first ratoon crop, and it is hoped that the final report will contain basic data for use in economic water studies.

CONCLUSIONS

The harvest results of the experiments and observation tests in the 1953 crop have brought out the following points:

1. Significant losses in both cane and sugar yields can be expected when irrigations are applied at soil moisture tensions of 0.65 atm. or higher.

2. No gain in sugar yields can be expected by irrigating at higher tensions prior to the normal ripening period during the second season of growth.

3. There is a strong suggestion of a thesis not yet proven by statistical analysis that increased yields might be expected when irrigations are applied at soil moisture tensions as low as 0.15 atm.

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EMERGENCY OVERHEAD IRRIGATION FOR UNIRRIGATED CANE

HENRY ALEXANDER AND JOHN MELLEN[1]

Use of water on sugar plantations is far from 100 per cent effective. The how, when, and where of irrigation must be determined by each plantation according to its needs. However, all irrigated plantations in Hawaii have one common problem: the uneven distribution of water in furrows.

This problem is aggravated during droughts. Six inches of water are usually applied to give an application of three inches in the lower sections of line. In the same soil during periods of extended irrigation intervals due to drought, an eight- to ten-inch application may be necessary to insure the three-inch minimum application. Under dry conditions, the remaining water supply does not cover as much area as it does under normal irrigation intervals.

Where the water supply is subject to wide variations, three ways of meeting this situation have been tried:

1. The plantation may plant only the area that can be adequately irrigated with the smallest amount of water that can be expected.
2. The plantation may plant all of the area for surface irrigation and plan to irrigate on a supplemental basis only that part of it which cannot be carried on regular irrigation schedules.
3. The plantation may plant part of its area for adequate irrigation, and plant the rest without furrows in the hope that normal rainfall will raise a satisfactory crop.

Each approach may be the most successful one under some special weather pattern. The first alternative may not make full use of the rainfall and the capital investment in the water supply. The second alternative is likely to be expensive in both layout and water, and may prove to be no better than the third alternative which is open to the greatest extremes of success or failure.

The use on an emergency basis of portable overhead irrigation on the area not laid out for surface irrigation offers a combination of the advantages of the two last alternatives as follows:

1. Relief is available for the unirrigated area in times of drought.
2. Irrigation of this area is possible without excessive use of water.
3. Maximum use is made of the water supply and of normal rains.
4. Investment in the overhead system is lower than the cost of preparing the area for surface irrigation when only five or six rounds are needed.

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5. Flat land culture of the regularly unirrigated area makes growing and harvesting the cane easier.
6. Better financial planning can be effected with a more stable production.
7. Dead and dying cane, which would otherwise increase milling and harvesting costs, are avoided.

At Kohala, periods of low rainfall occur frequently enough to reduce yields on 1600 acres of unirrigated area by 25 to 50 per cent of what is grown in seasons with the normal annual rainfall of 45 to 55 inches. At one time, much of this area was laid out for surface irrigation, but it became apparent that there was not enough water to provide this irrigation. By 1946, the entire 1600 acres were planted without furrows.

Yields from these fields have varied widely. At times, they have given good yields and have produced sugar at low cost. At other times, the yields have been near-failures as the result of droughts. Following the 1951 drought, there were large areas where 40 to 50 per cent of the cane was dead. At harvest, the juices of these fields had a ratio of 15 to 17 tons of cane per ton of sugar. By slowing down the grinding rate, this made other cane overage at harvest and aggravated the situation. As a result of this drought, fields which would have yielded five to seven tons of sugar per acre did not yield more than three to four tons of sugar at harvest.

This was not just "unusual weather." This dry weather should be expected in four or five out of every 10 years. A practical solution had to be found to meet these dry seasons.

Therefore, to supply emergency irrigation for 400 acres of 12 to 18 month-old cane in each crop, Kohala has invested $25,000 in sufficient portable overhead irrigation equipment to cover this area once a month during dry spells.

Field preparation for overhead irrigation starts during the off-season with trial layouts on a contour map of the field. Much planning and preparation must be made in advance to permit effective use of water, manpower, and machine time. Sumps, eight feet deep and four by six feet across, must be dug in the ditch to provide a reservoir for the pump. The paths for the pipe must be pushed back during wet weather to avoid breaking cane.

The use of the emergency overhead irrigation is begun when field observations and Bouyoucos blocks both indicate that the soils are near the wilting point. In order to get over the entire area before the cane starts to die, irrigation is begun before the available soil moisture is depleted.

Kohala's emergency irrigation equipment consists of a trailer-mounted, Diesel-driven pump, 8-inch aluminum tubing for the main line, 6-inch aluminum tubing for the laterals and 1⅛-inch sprinklers. (Figure 1) In order to avoid excessive pressures, a trailer-mounted pressure breaker is installed in the main line on steep hills. Elbows, angle pipe, and other special fittings are needed to get into odd corners of fields and over or around rock piles. Miner's lamps are used at night to aid in 24-hour operation of the system. To make attendance at the engine unnecessary, a safety switch, installed on the discharge side of the pump, automatically shuts down the Diesel engine if the pump loses its prime or a break in the pipeline occurs.

An effective two-inch application of water is secured by applying 3.5 inches with closely-spaced risers. (Figure 2) Some areas within the pattern receive 4.25

Figure 1. Type of sprinkler used at Kohala for emergency overhead irrigation.

Figure 2. Sprinklers are spaced closely enough to apply two inches of water effectively.

inches. If there is no wind, 2.25 acres can be covered by each sprinkler. In order to get effective irrigation in winds up to 15 miles per hour, only half an acre is allowed per sprinkler in the layouts at Kohala. To insure sufficient application, sprinklers are run one and one-half hours in one setting. This provides a maximum coverage of 0.9 acres per hour with three sprinklers and 1.2 acres per hour with four sprinklers. Allowances have to be made for breakdowns and delays in moving between areas. Three sprinklers are operated at a time when pumping uphill. Four sprinklers can be operated at a time when pumping downhill. Water is delivered to the pump at the rate of two million gallons per day when four sprinklers are running. This allows a small overflow at the sump.

The sprinklers are operated on one lateral, while a lateral and sprinklers on the other side of the main line are being set up. When the new lateral is ready and the first sprinklers have run the desired length of time, the water is turned into the new lateral and the first lateral is moved up the field.

A crew, made up of three overhead irrigators and one senior irrigator, is required to set up a lateral and three new sprinklers every hour and a half. In order to hold "down time" on the pump to a minimum, additional men are brought in to help move the main line when the pump is changed to a new area. At a time when the weeds are partially checked by the drought, men from the Weed Control Division help in the operation of the system so that the high labor requirement of slightly less than an acre per man-day is not a drain on other operations. At this time, no other work could be more productive than keeping the cane alive.

Portable overhead irrigation is more economical than surface irrigation when up to five or six rounds of irrigation are needed to grow a satisfactory crop. If the excessive water, which is used in surface irrigation to get a round through the cane when the soil dries out, is charged against the surface irrigation at the value of water at that time, portable overhead irrigation would be less costly up to nine or ten rounds of irrigation.

There are many operating problems still to be solved in the use of portable overhead irrigation as an emergency relief for unirrigated fields. Improved layouts can reduce the handling of the pipe, silting of the sumps can be avoided by placing these reservoirs to one side of the supply ditch, and "down time," due to equipment failure, can be minimized with improvements in design. Hidden costs which are inherent in the system are as follows:

1. Money spent to start the operation only to have it rain within a few days.
2. Sump preparation and pushing back for emergency irrigation done needlessly in what turns out to be a wet year.
3. Inefficiencies associated with frequent start-stop operations.
4. Water usually taken from regular surface irrigation at a time when water is in short supply.

However, after the first season of use, Kohala Sugar Company can report that there is a place for the emergency relief of unirrigated cane by portable overhead irrigation in the area of 45 to 55 inches annual rainfall. This system is not meant to replace surface irrigation where regular rounds are needed throughout the year. Because the system can be expected to save 1½ to 2 tons of sugar per acre with three or four rounds, it can be considered one of the best ways to put the stockholder's money to work—saving the cane from dying, saving the sugar that already has been grown by normal rainfall.

If there are unirrigated areas which suffer during droughts while adjacent irrigated areas grow normally, or if there is irrigated land which can grow satisfactory unirrigated cane if given a few emergency irrigation rounds, then the overhead system may have a place in the irrigation plan. It is hoped that the installation at Kohala is one more step toward more effective use of water on sugar plantations.

THE METEOROLOGICAL APPROACH TO IRRIGATION CONTROL

L. D. BAVER[1]

Present-day irrigation control consists of following the depletion of soil moisture on the moisture-tension curve until it reaches the tension desired as an indicator of the time to irrigate. Moisture changes can be followed by making soil moisture determinations, ascertaining the change in resistance of porous blocks placed in the soil or following the change in tension of tensiometers. Several investigators have suggested that soil moisture depletion and, consequently, irrigation intervals, can be calculated from meteorological data. Das (3, 4) made one of the first attempts to establish irrigation practices on weather factors by introducing the concept of the "day-degree". He defined day-degrees as the number of degrees Fahrenheit between the daily maximum temperature and 70°. The accumulated day-degrees were the sum of the daily day-degrees for chosen periods. Numerous field experiments were conducted in Hawaii to measure the relationship to sugar yields of the number of day-degrees between irrigations. About 350 day-degrees between irrigation intervals appeared to be optimum. Several plantations have used this method for controlling their irrigation practices. Shaw and Swezey (8) observed that the relation of cane growth to day-degrees varied from period to period throughout the growth of the crop. They found no consistent relationship for the number of day-degrees accumulated between irrigation and the point of moisture exhaustion. The major weakness of the day-degree is rather obvious. The difference between the maximum temperature and 70° may be the same on two consecutive days but the length of time during which this difference existed may vary over 100 per cent. There may or may not be a relationship between the number of day-degrees and the total amount of solar energy reaching the earth on two different days.

Evapotranspiration data are the basis for more recent attempts to determine irrigation intervals from meteorological data. It is essential to review briefly some of the researches contributing to the calculation of evapotranspiration. Thornthwaite (10) introduced the term "potential evapotranspiration" to express the combined effects of evaporation and transpiration. It is defined as the amount of water which is lost from a surface completely covered with vegetation when there is sufficient water in the soil at all times for the use of the vegetation. The rate of evapotranspiration is dependent upon climate, soil-moisture supply, plant cover, and land management. The first two factors are considered the most important. Temperature, humidity and wind velocity are considered the main climatic factors

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responsible for evapotranspiration losses. An empirical method has been suggested to calculate potential evapotranspiration from climatological data. The first step is to determine the heat index, I. This is obtained from a summation of the monthly values of an index "i" dependent on the mean monthly temperatures in C°. The monthly index is obtained from the equation $i=(t/5)^{1.514}$. The second step is to obtain the unadjusted potential evapotranspiration from the equation

$$e=1.6\ (10t/I)^{a} \qquad (1)$$

where e = monthly evaporation in centimeters
t = mean monthly temperature in C°
I = heat index
a = coefficient that varies with heat index.

Thornthwaite observed a linear relation between the logarithm of the temperature and the logarithm of the unadjusted potential evapotranspiration. Consequently, he has prepared a nomogram for obtaining evaporation data from Equation 1. The third step is to adjust the unadjusted potential evapotranspiration values for day and month lengths. A table is given from which the adjusted values may be obtained. After following these empirical steps, one has a calculated value of the potential evapotranspiration for the area. Thornthwaite has perfected a technique for measuring these values in situ but the equipment is elaborate and expensive.

For continued evaporation, there must be a supply of energy to provide the latent heat of evaporation and a mechanism for removing water vapor from the evaporation area. Penman (5) has suggested the following semi-empirical equation to calculate the rate of evaporation from wind velocity and vapor pressure data:

$$E_o=0.033\ v^{0.68}\ (e_s-e_d)\ \text{mm./day} \qquad (2)$$

where e_s is the mean saturation vapor pressure at the water surface, determined by the mean surface temperature, T_s; e_d is the mean vapor pressure in the air at the dewpoint temperature; v is the wind velocity in miles per day measured at two meters above the ground level. This equation suggests that evaporation is a function of the vapor pressure gradient between the surface and the air above.

Penman also has emphasized the importance of energy changes in promoting evaporation. Evaporation requires energy to supply the latent heat of vaporization. Penman divided the process into two phases. He developed an expression for the total amount of energy available for evaporation and heating of the air and divided the energy so obtained between the evaporation and heating processes. His final equation was

$$E_o=(\triangle H+0.27E_a)/(\triangle+0.27)\ \text{mm./day} \qquad (3)$$

where E_a is the evaporation when the saturation vapor pressure is that at air temperature, H is the total available energy in mm. per day, and $\triangle$ is the slope of the evaporation-temperature curve when T is at air temperature. Mean air temperature, mean air vapor pressure, mean wind velocity and mean duration of sunshine are required to calculate the evaporation.

E_a is calculated from the equation

$$E_a=0.35(1+9.8\times10^{-3}v)\ (e_a-e_d) \qquad (4)$$

E_o can also be calculated from the equation

$$E_o=\frac{H}{1+.27(T_s-T_a)/(e_s-e_d)} \qquad (5)$$

Penman found that evaporation from a free water surface approximated that from the soil or from certain types of vegetation. Evaporation from grass over a period of a year was about 75 per cent of that from open water. There was a seasonal variation in this relationship. During the winter months with about 9.5 daylight hours, the ratio of evaporation from grass to that of water was 0.6; in the spring and fall with about 13 hours of daylight, the factor was 0.7; and during the summer with 16.5 daylight hours, it was 0.8. The principal reason given for the change in the ratio with season was the closing of the stomata at night, which interrupted transpiration. The nature of the vegetation played a small role. Fertilized grass with three times the amount of vegetative canopy as unfertilized gave the same ratio. Ripened corn or trees would not be expected to give the same results as a growing crop. He has postulated the same ratio for the tropic, subtropic and temperate regions.

Schofield and Penman (6) have analyzed this concept in relation to vegetation and concluded that evaporation from vegetation depends more on the acreage than on the integrated leaf area. This is because of the close relationship between evaporation and the amount of solar radiation incident upon the vegetative canopy. The length of day and the distribution of bright sunshine would then be the major climatic elements to consider in an analysis of evaporation. Of course, unless evaporated water diffuses into the surrounding air, evaporation would cease because of a saturated layer of air above the evaporating surface. Consequently, the turbulence of the air is an important factor in disturbing the vapor pressure gradient between the surface of the soil or vegetation and the upper air. However, over an entire year, they consider turbulence to be much less important than sunshine which supplies the energy for evaporation.

Baver (1) in an analysis of the evaporation data from 243 monthly records from 29 meteorological stations throughout the United States, found that evaporation from a free water surface varied approximately with the square of the mean monthly temperature in Fahrenheit degrees

$$E = T^2/1000 \qquad (6)$$

Recently, Baver analyzed the evaporation and meteorological data from Oahu Sugar Company and found an exceedingly close correlation between solar energy and evaporation. Wind and temperature effects showed poorer correlations. These data are shown in Figure 1.

Let us now take this background information and see how it can be applied to irrigation problems. Thornthwaite (9, 10, 11) has suggested that a daily account be kept of the amount of available water in storage in the root zone in order to determine not only the irrigation interval but also the amount of water to apply. He first utilized mean monthly values of potential evapotranspiration and precipitation and obtained a water balance showing evapotranspiration, water deficiency, water surplus and runoff. A typical water balance graph for Pullman, Washington, is shown in Figure 2. It is seen that there is a surplus of water in the winter months when there is no evaporation or water usage and precipitation is high. Evaporation and precipitation are about equal during the latter part of March and September. Due to an abundance of water in the soil in the spring, most of the precipitation up to April 1 is surplus water. The precipitation in the fall of the year during October and November is used to recharge the soil moisture supply. There is a deficiency of precipitation between April and October. The soil storage

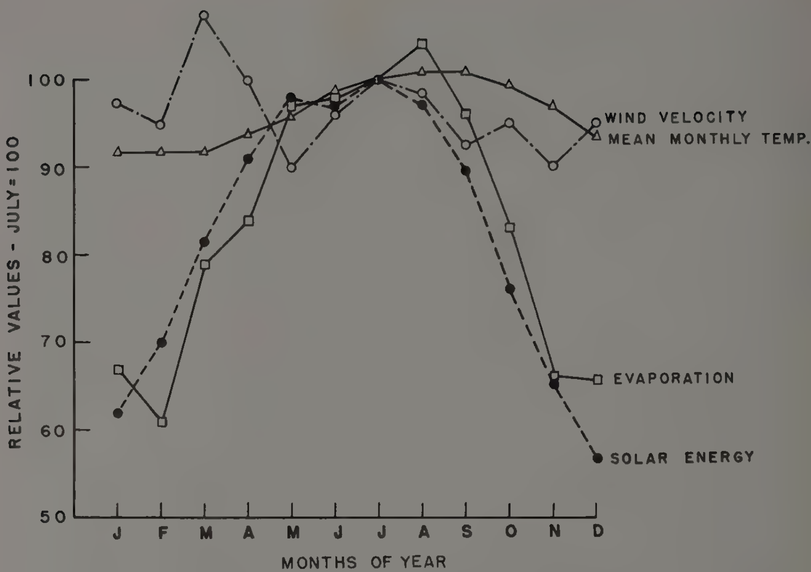
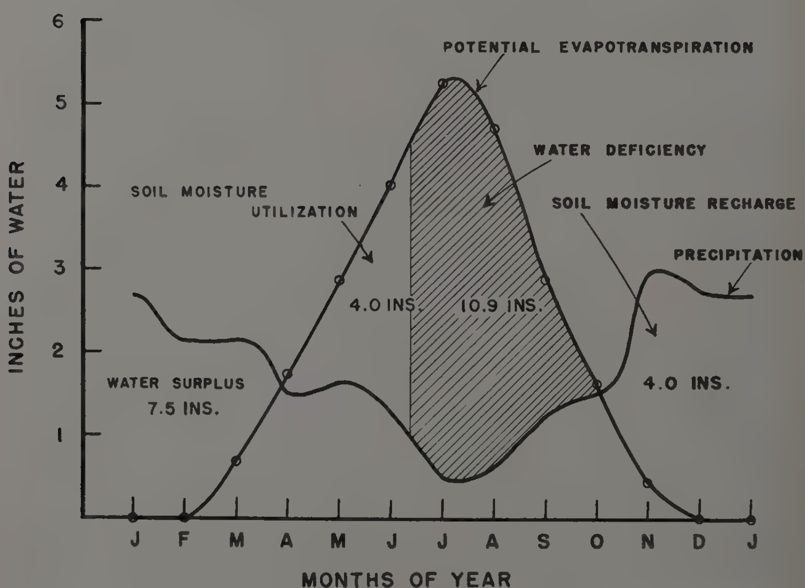


Figure. 1 Relation of evaporation to meteorological factors.

Figure 2. Water balance chart for Pullman, Washington.



supply is used up by about the first part of June and an actual water deficiency then exists until October.

The aforementioned principles are used by Thornthwaite on a daily basis for irrigation control. He states that the soil reservoir can only provide about 10 cm. of water for plant usage irrespective of the type of soil. Although this statement is not valid, because of the varying moisture-tension curves for different soils as previously discussed, it does not affect materially the use of meteorological data to calculate the irrigation needs of soils. The moisture-tension curve of a soil will give the true value of the soil storage supply which should be used in lieu of 10 cm. The fundamental thesis of Thornthwaite's concept is as follows:

> "In order to evaluate the daily soil moisture balance one must first find a period in which the soil either contains the full 10 cm of moisture or is completely dry. Starting, thus, with either 0 or 10 cm of soil moisture storage one need only compute from data of mean air temperature and day length the daily water loss by evapotranspiration and measure any additions of moisture to the soil by precipitation. Since the soil moisture content cannot go over 10 cm or under 0 it is clear that any precipitation producing a net amount of stored soil moisture of over 10 cm can not be included while evapotranspiration during periods with no stored soil moisture is considered zero. Through a simple bookkeeping procedure the daily accretion and depletion of the soil moisture content can be determined. Supplemental irrigation can be scheduled to prevent the soil moisture from falling below any desired lower limit. Irrigation is called for anv time the soil moisture computations reveal that the amount of water in the soil is below a certain minimum determined from the particular crop. The amount of irrigation water to be applied is also determined for the particular crop on the basis of the optimum level of soil water desired to be maintained."

A typical water budget for a month is given in Table 1. Here, Thornthwaite calls particular attention to the fact that daily evapotranspiration and precipitation values give a different picture than that given by individual mean monthly values. Using mean monthly values of evapotranspiration and precipitation and the empirical value of 10 cm. for water storage, it is observed that there was a surplus of 7.1 cm. and no deficiency. However, on a daily basis, there was a surplus of 11.2 cm. and a deficiency of 2.6 cm. during the month. These differences can be explained by the fact that periods of deficiencies and surplus rarely occur in succession during the month.

Thornthwaite has found close agreement between soil moisture computed from temperature data and that obtained from soil moisture samples or gypsum block readings. He has found mean monthly or daily temperature and day length to be the only meteorological data necessary because "satisfactory results could be obtained without the use of wind, humidity, or solar radiation" since "these important influences on evaporation including temperature vary together." Computations of evaporation in Hawaii indicate that mean monthly temperatures are not adequate to give a true picture of the process. Evaporation is much more closely related to solar energy. Mean monthly temperature probably is more useful under continental conditions where it is so closely related to the amount of

Table 1.

WATER BUDGET AT SEABROOK, NEW JERSEY, SEPTEMBER 1950

(Thornthwaite, 11)

Date	Potential Evapotranspiration	Precipitation	Storage Change	Storage in Soil	Water Surplus	Water Deficiency
	cm.	cm.	cm.	cm.	cm.	cm.
1	.50	....	—.50	.04	0	0
2	.52	.08	—.04	0	0	.40
3	.43	.46	.03	.03	0	0
4	.41	....	—.03	0	0	.38
5	.24	....	0	0	0	.24
6	.28	....	0	0	0	.28
7	.28	....	0	0	0	.28
8	.33	....	0	0	0	.33
9	.35	....	0	0	0	.35
10	.39	....	0	0	0	.39
11	.33	16.92	10.00	10.00	6.59	0
12	.26	....	—.26	9.74	0	0
13	.22	.38	.16	9.90	0	0
14	.27	3.81	.10	10.00	3.44	0
15	.31	....	—.31	9.69	0	0
16	.28	....	—.28	9.41	0	0
17	.20	....	—.20	9.21	0	0
18	.21	....	—.21	9.00	0	0
19	.30	.08	—.22	8.78	0	0
20	.26	....	—.26	8.52	0	0
21	.26	.13	—.13	8.39	0	0
22	.22	2.92	1.61	10.00	1.09	0
23	.25	.33	0	10.00	.08	0
24	.09	.08	—.01	9.99	0	0
25	.09	....	—.09	9.90	0	0
26	.12	....	—.12	9.78	0	0
27	.15	....	—.15	9.63	0	0
28	.18	....	—.18	9.45	0	0
29	.19	....	—.19	9.26	0	0
30	.27	.13	—.14	9.12	0	0
Total	8.19	25.32			11.20	2.65

sunshine. The method of Thornthwaite is being used to control supplemental irrigation on 19,000 acres of vegetable crops in New Jersey.

Schofield and Penman (6) also have applied the concept of soil moisture deficit, calculated from Penman's (5) evaporation equations, to both drainage and irrigation problems. An example of their data is shown in Figure 3. The field capacity of the soil is shown by the solid horizontal line; the readily available water is indicated by the dotted line; the period when the drains were running is shown by the thicker portions of the line at zero deficit. These data were obtained on a rapidly draining soil in which a tile drainage system had been installed. It is significant to note that water in the drains begins to flow when the deficit curve (precipitation minus estimated evaportanspiration) intersects the field capacity line. From March through May and from the middle of October through the early part of December, there is adequate available water in the soil for optimum plant growth. A definite water deficiency for plant growth is exhibited during the summer months when supplemental irrigation is necessary to raise the available water supply of the soil. Schofield (7) has reported significant increases in the yield of sugar beets from overhead irrigation during this period.

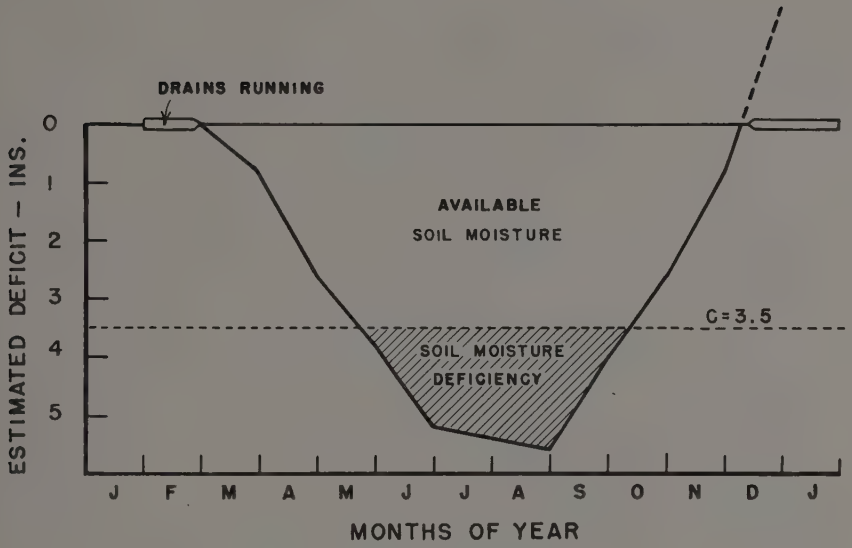


Figure 3. Water balance chart at Cambridge University Farm, England.

Blaney and Criddle (2) have developed a formula for calculating the evapotranspiration based essentially upon mean monthly temperature and daytime hours.

$$U = KF = \text{sum of } kf \qquad (7)$$

where U = consumptive use (or evapotranspiration) in inches for any period
F = sum of the monthly consumptive-use factors for the period
K = empirical consumptive-use coefficient (growing period)
k = monthly consumptive-use coefficient
f = monthly consumptive-use factor $= t \times p/100$
t = mean monthly temperature, F°
p = monthly per cent of daytime hours of the year

This method has been used to calculate the consumptive use of water by alfalfa and other crops in western United States.

Van Bavel and Wilson (12) have applied the concepts of Thornthwaite and Penman to the irrigation of tobacco on a coarse sandy loam in North Carolina. They first determined from the moisture-tension curve of the soil that there were 1.50 inches of usable water in the upper 12 inches of soil. The calculated daily evapotranspiration rate in the area was 0.21 inches. Tensiometers were installed to check the need for irrigation. Over a period of two summers, there was only one instance out of 10 when the scheduled irrigations from the two methods varied by more than one day.

The meteorological approach to irrigation has the advantage of simplicity of operation when compared with methods based upon measurement of soil moisture changes. If it is proved satisfactory, the costs of using this system would be rela-

tively small. Undoubtedly, new techniques will be developed that will give an integrated measure of daily temperature, sunshine and solar energy. When such methods are available, meteorological data can be correlated better with evapotranspiration.

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